Higgs & BSM contributions

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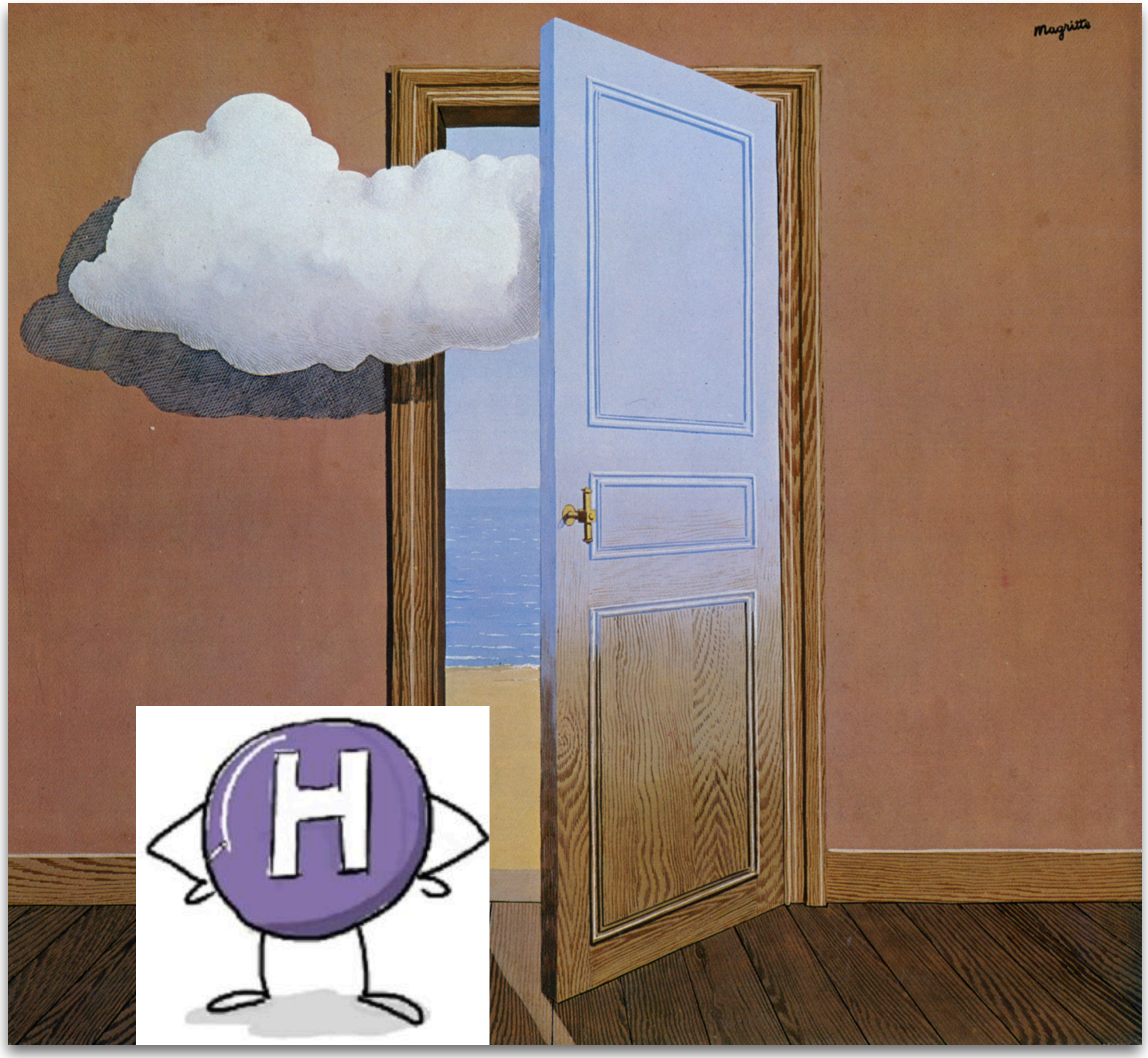
Energy Frontier Workshop @ Brown University

U.S. DEPARTMENT OF ENERGY
Office of Science

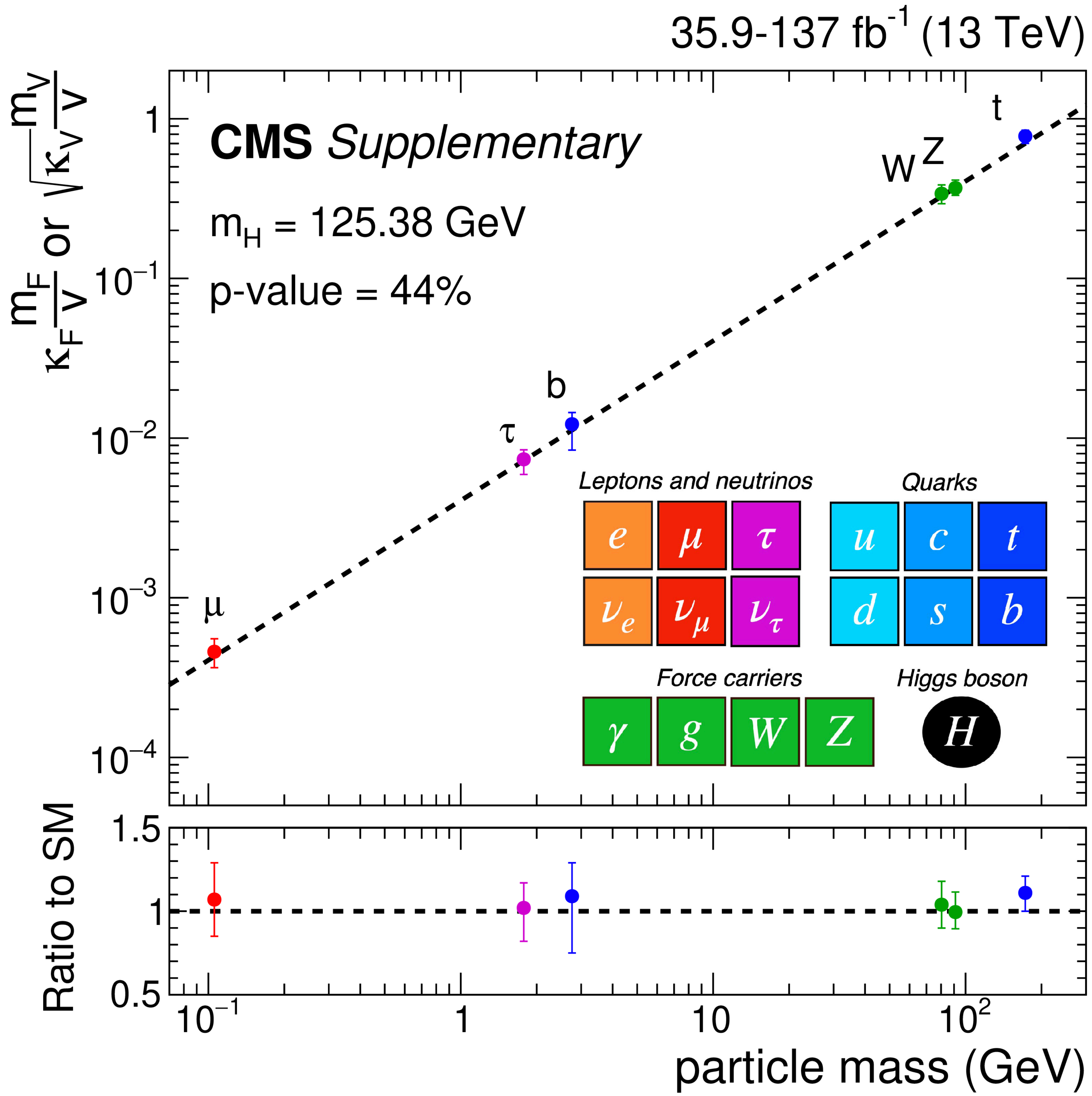
SLAC NATIONAL ACCELERATOR LABORATORY

Higgs and the exploration of the EF

- The Standard Model is not a complete theory
  - Gravity, neutrino mass, dark matter …
- The Higgs boson is a **potential window to probe physics Beyond the Standard Model**
  - Searches for additional scalars
  - (Interplay with) Precision measurements of the **Higgs boson properties**
    - Higgs Global fits



Higgs in 2022



m_H = 125.38 ± 0.14 GeV

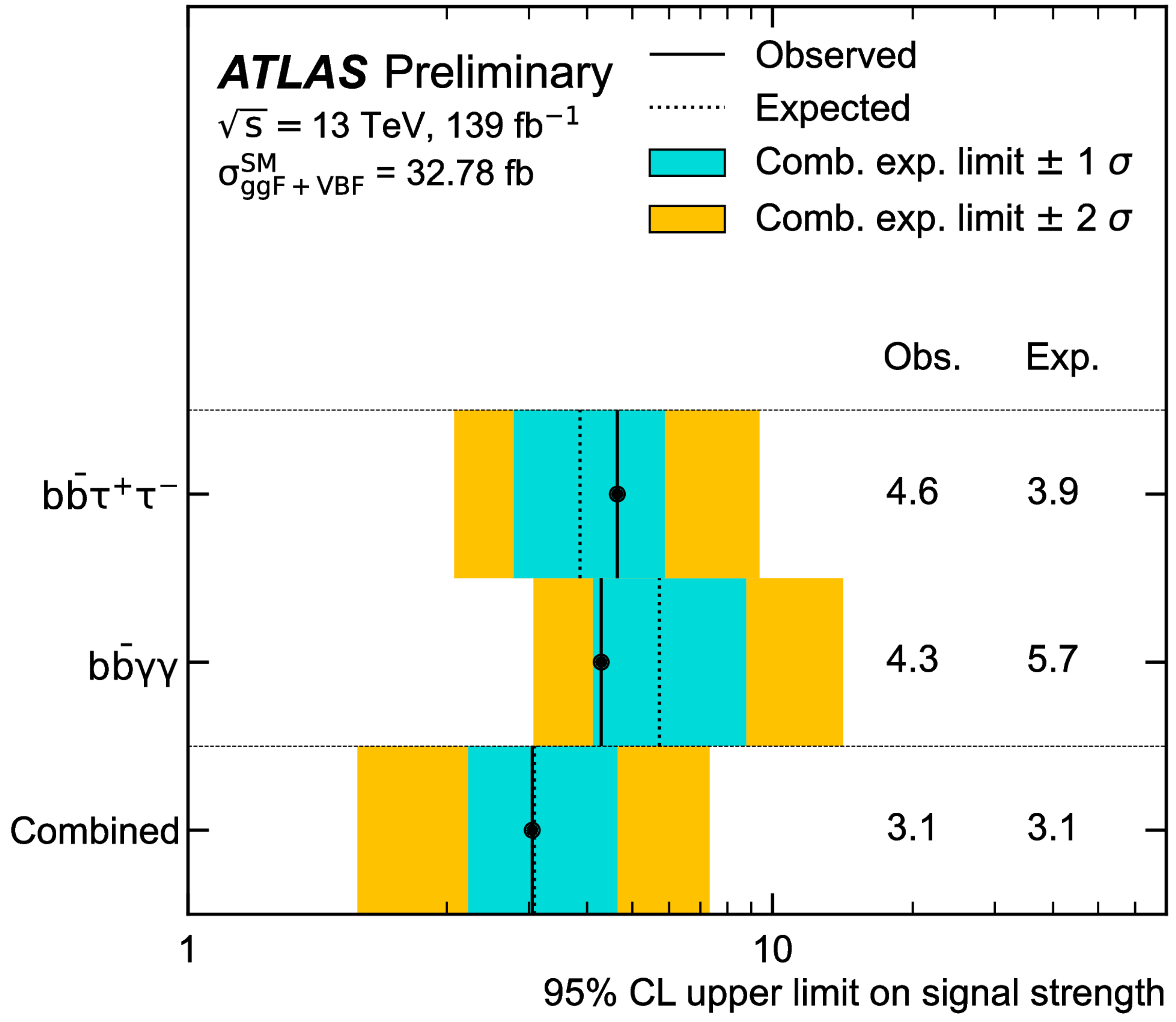
Phys. Lett. B 805 (2020) 135425

BR(inv.) < 0.17 (0.11)

CMS-PAS-HIG-20-003

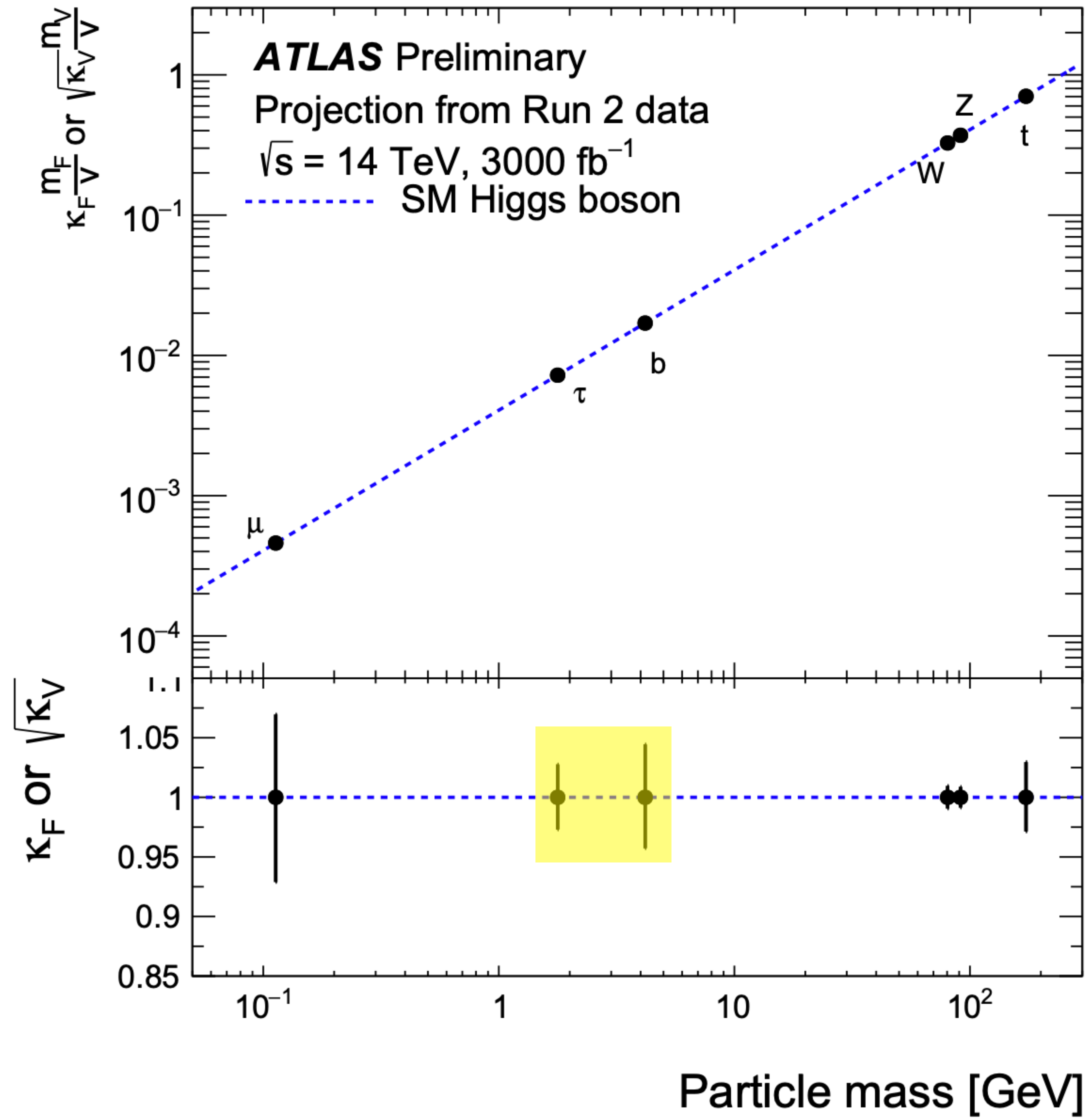
|κc|<3.4

CMS-PAS-HIG-21-008



LHC → High Luminosity LHC

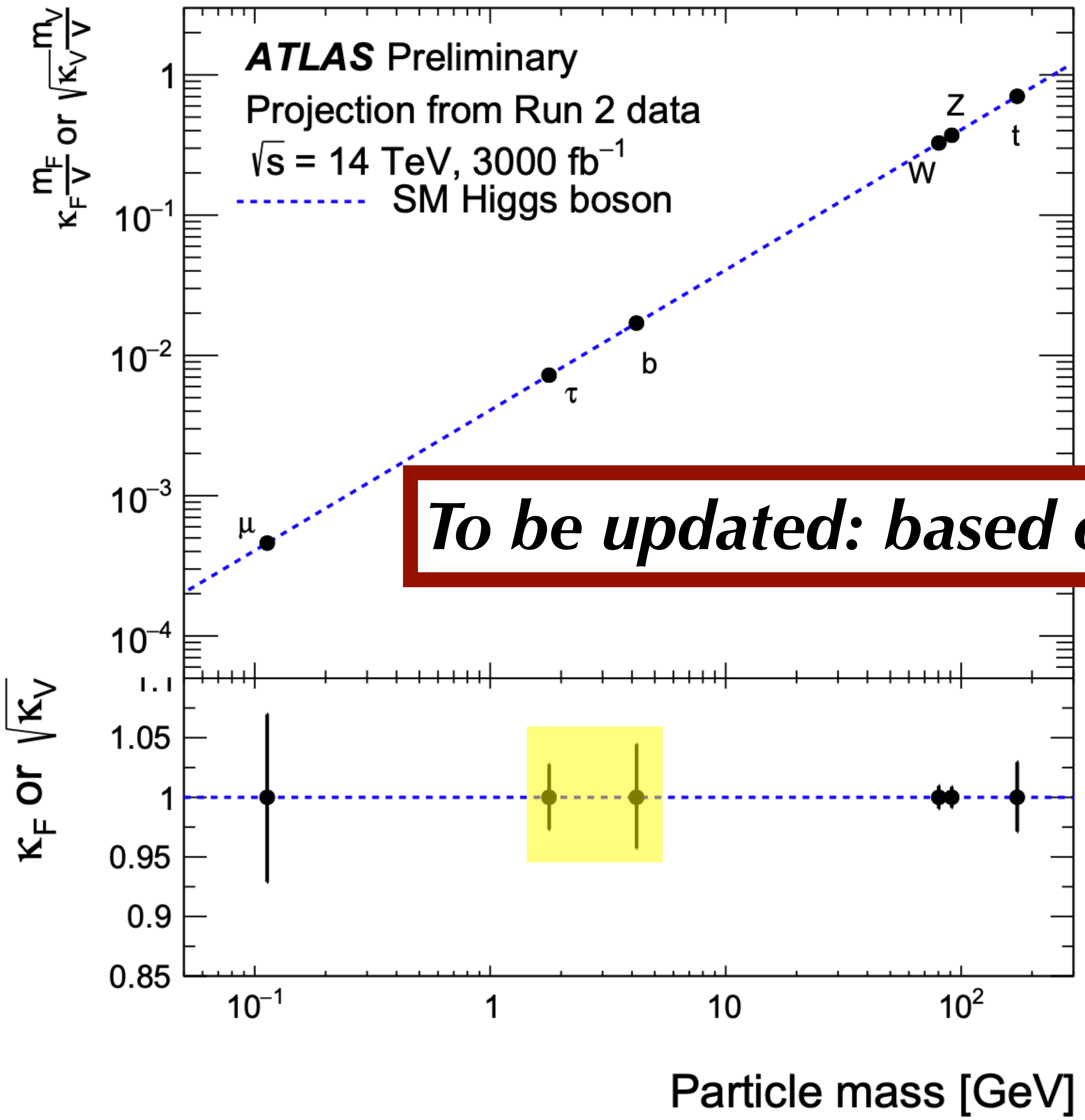
Higgs physics at the HL-LHC



The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for most of Higgs couplings**
- **Larger uncertainties on Zγ and charm**
- **<50% on the self-coupling**
- **Higgs width 5%**

Higgs physics at the HL-LHC



The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for most of Higgs couplings**
- **rm**
- **<50% on the self-coupling**
- **Higgs width 5%**

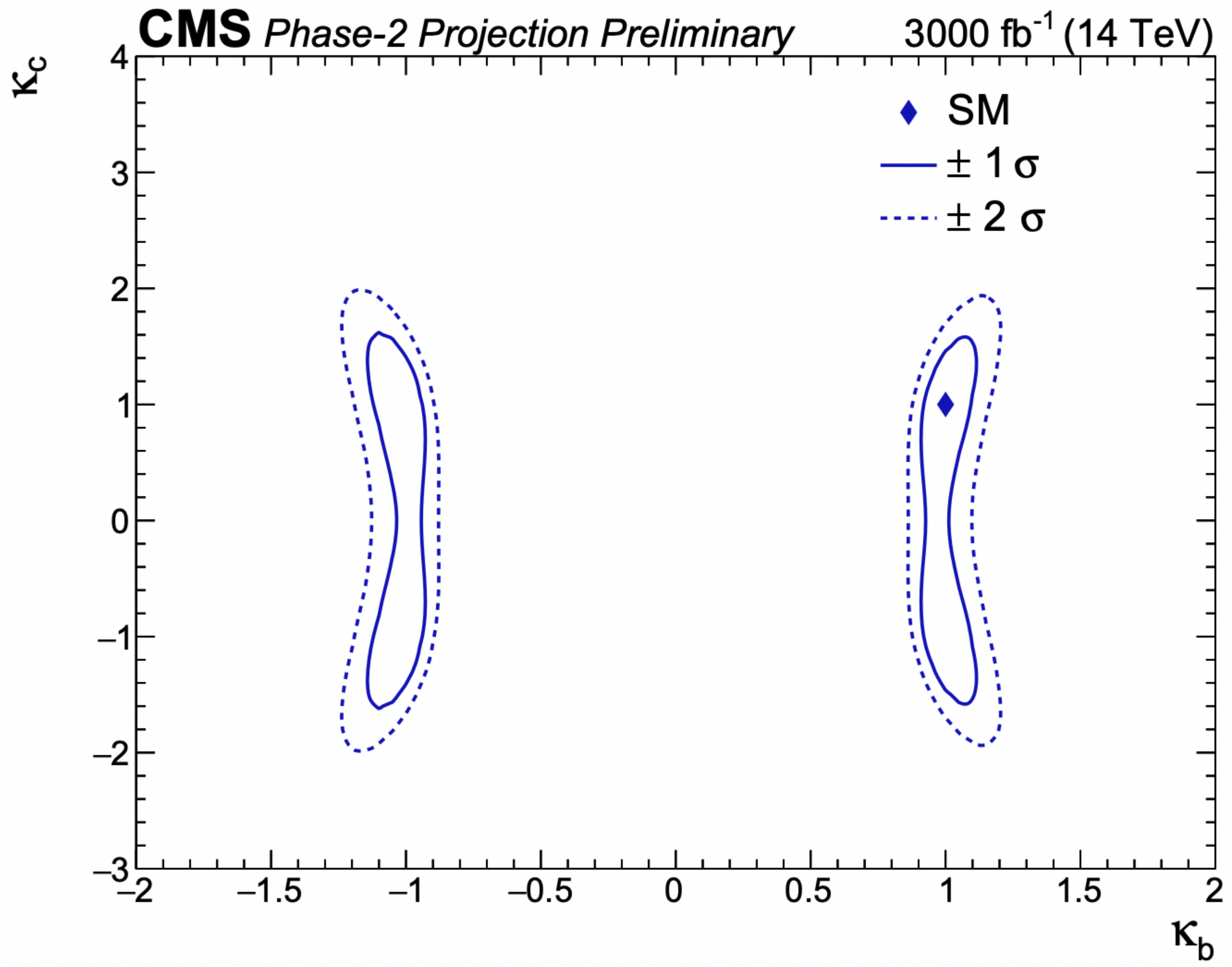
To be updated: based on the new studies for Snowmass

Higgs physics at the HL-LHC

ATLAS+CMS HL-LHC 2022 study

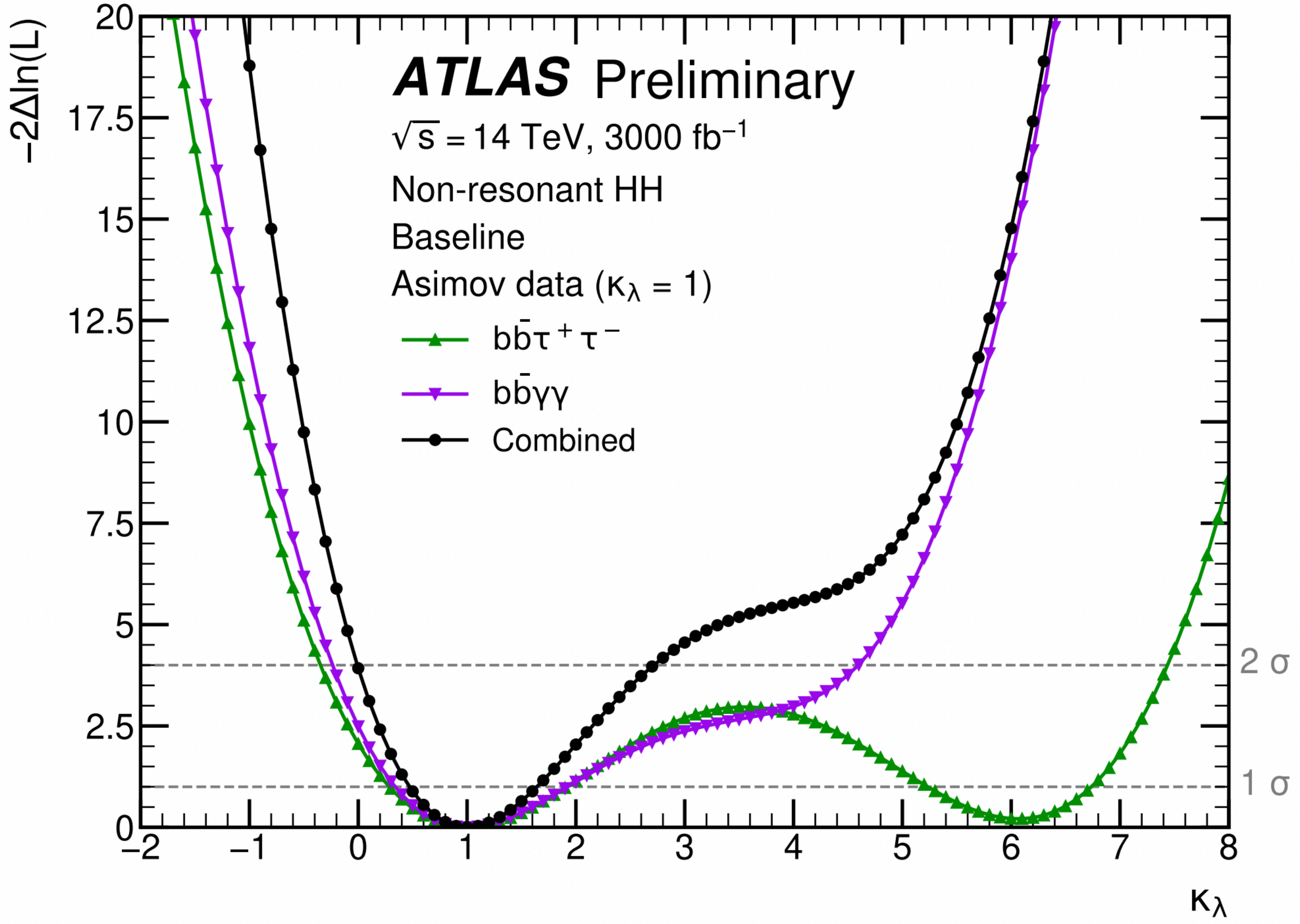
Sapta's and Quentin's talks

NEW!



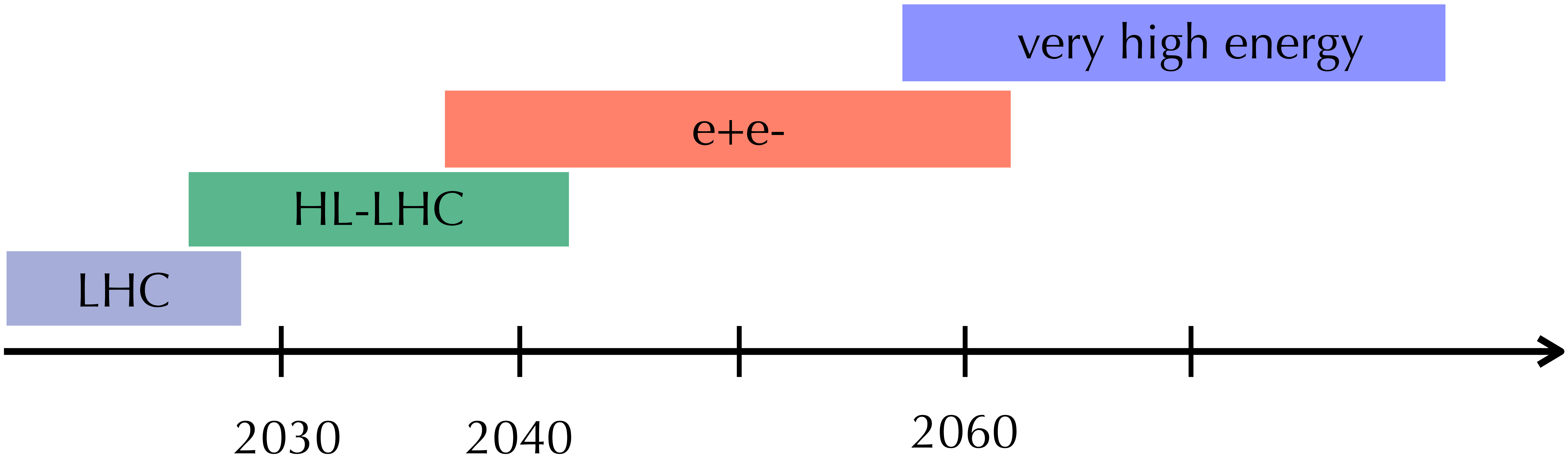
First extrapolation of κc

NEW!



From 3.3σ to 4.6σ on the expected SM σ_{HH}

Higgs as a guide

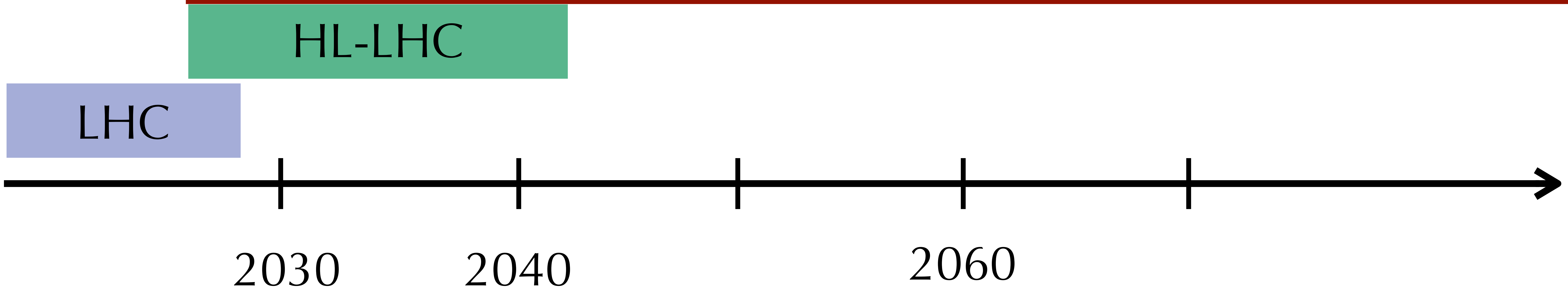


H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

Higgs as a guide

Wish list beyond HL-LHC:

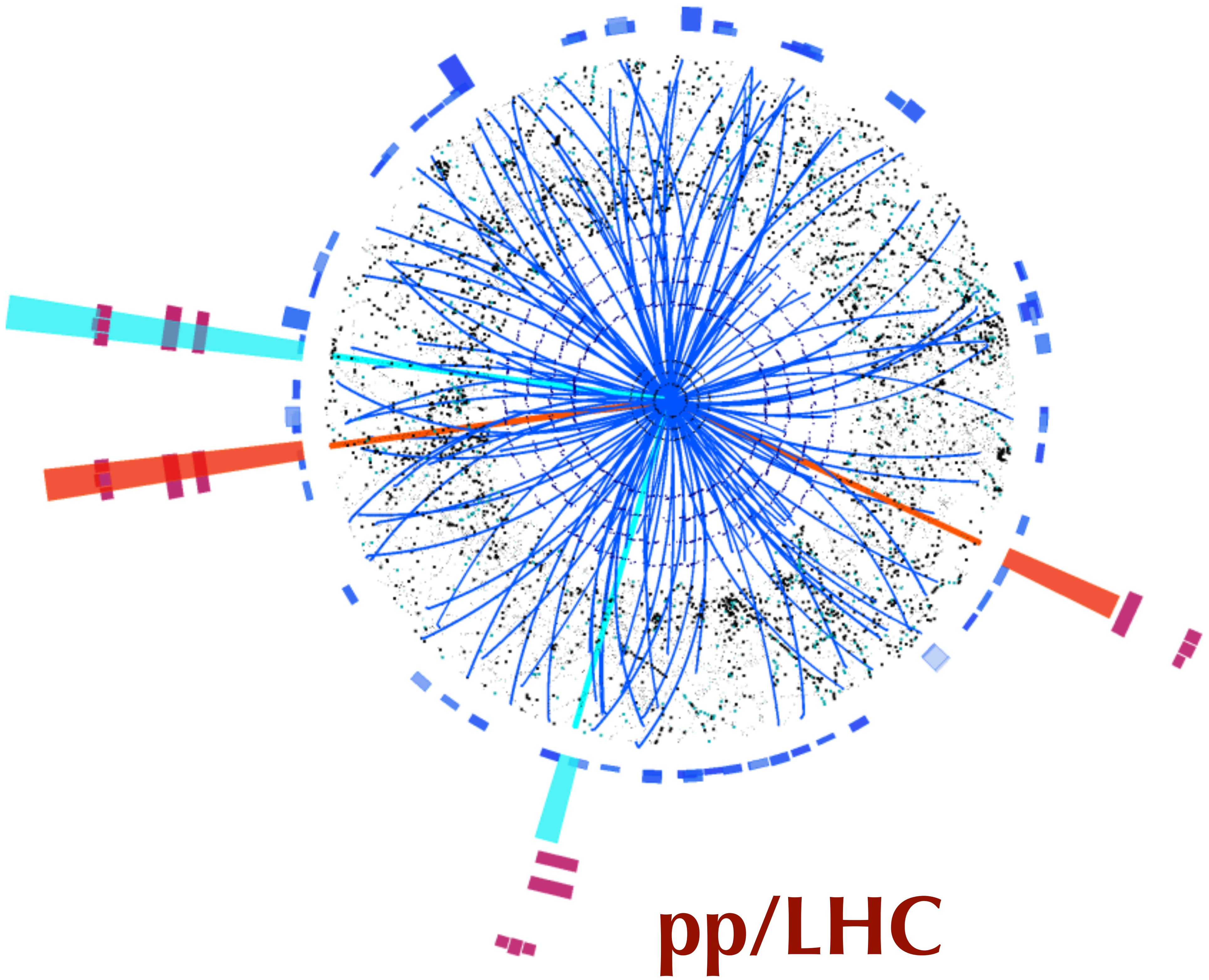
1. Establish Yukawa couplings to light flavor $\Longrightarrow$ precision & lumi
2. Establish self-coupling $\Longrightarrow$ high energy



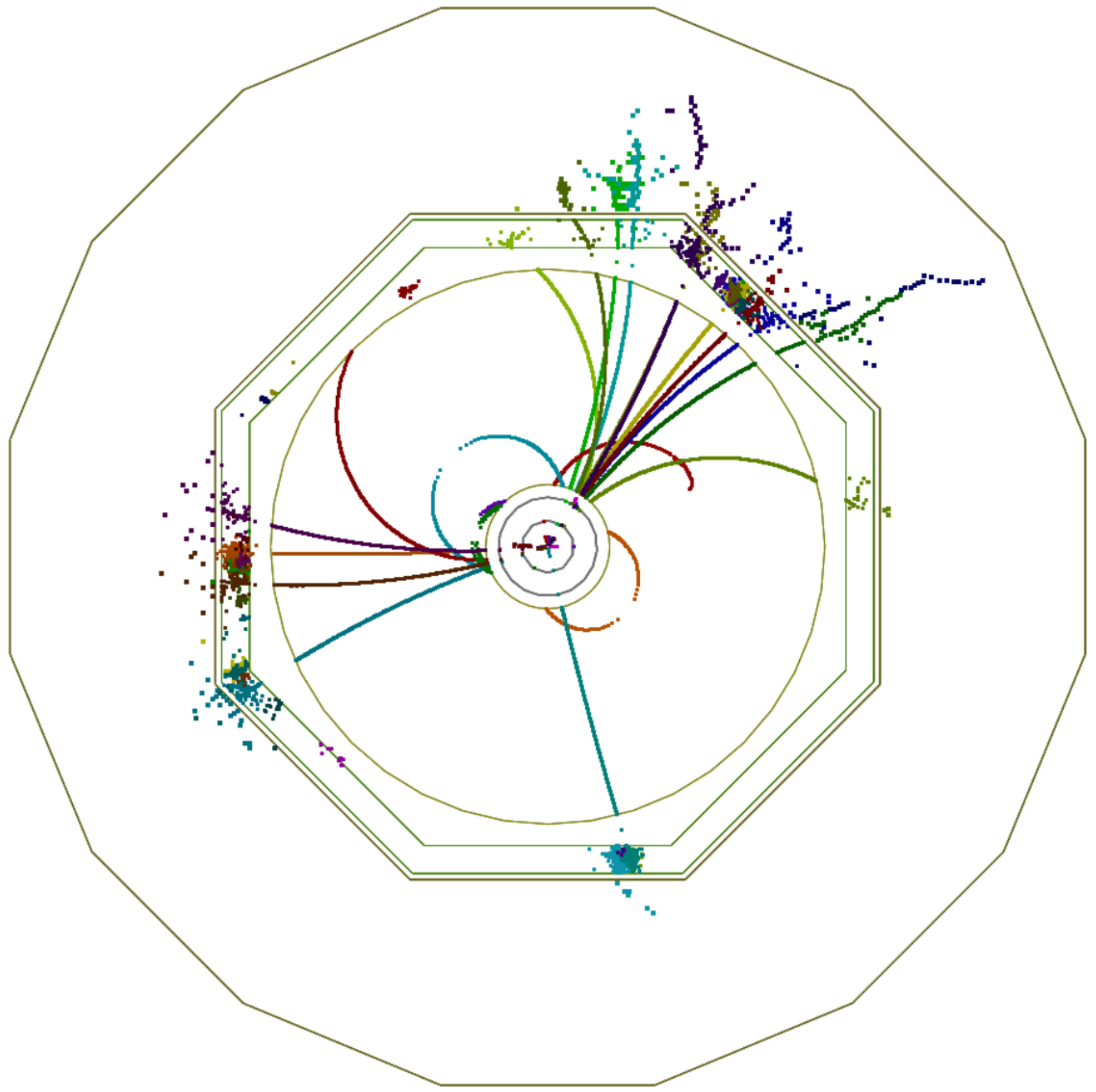
H couplings to:	O(5-15)%	O(0.1-1)%	O(1)‰
H self-coupling to	<O(50)%	O(20)%	O(1)%

Why leptons?

- Initial state well defined (& polarization) ⟹ High-precision measurements
- Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and trigger-less readout

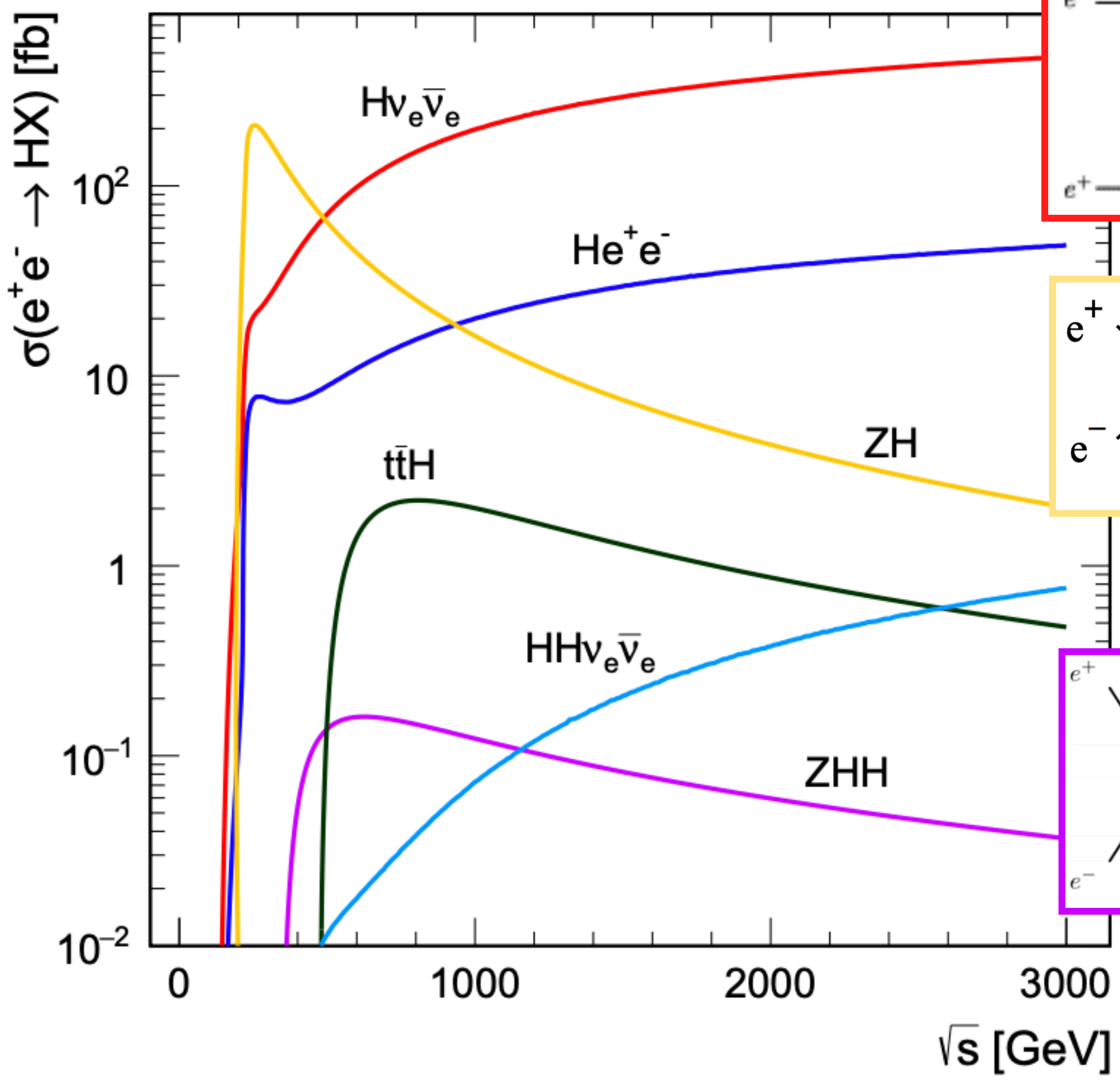


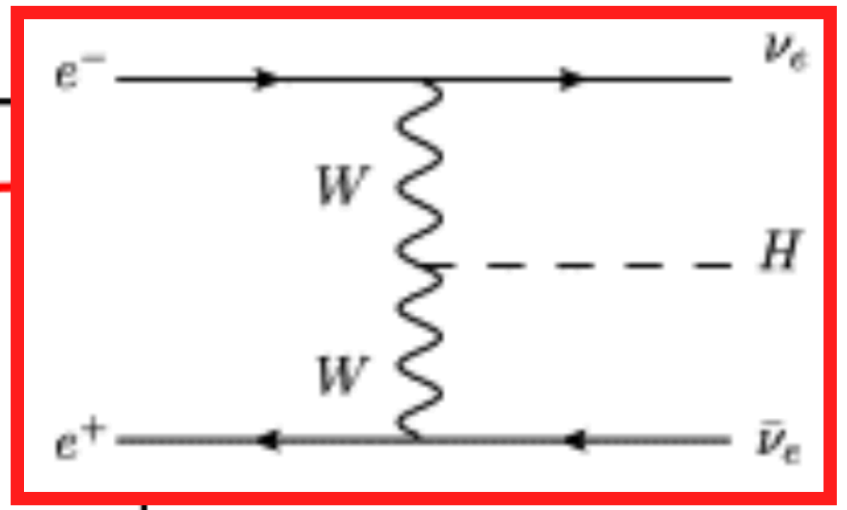
pp/LHC

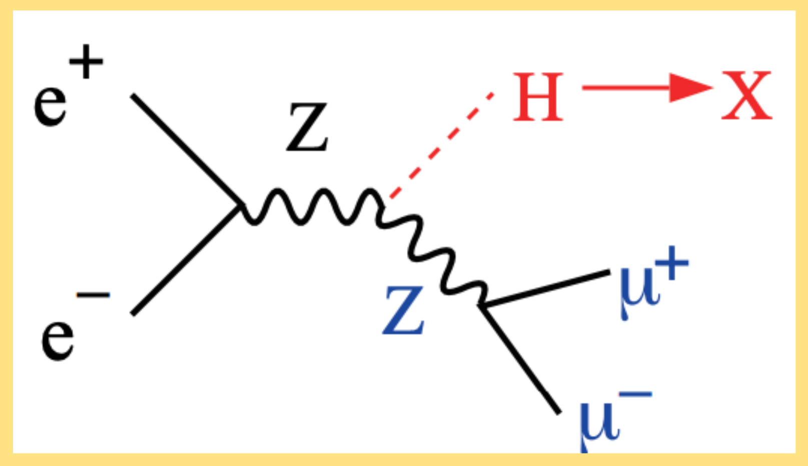


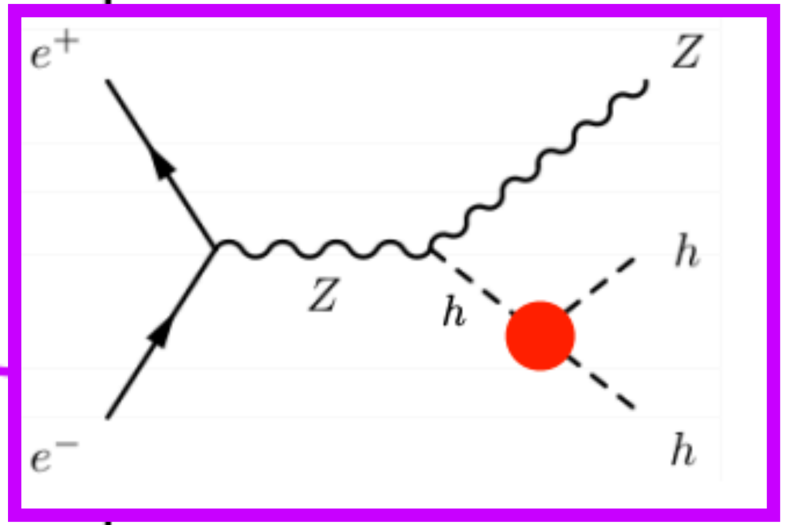
e^+e^-

Higgs at e+e-









- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - Hvv dominates
  - ttH opens up
  - HH production accessible with ZHH

Exploring the complementarity between e^+e^- and LHC will lead to the most precise measurements

- ***What do we want to learn on top of what HL-LHC will deliver?***
- ***Timelines matter - ideally the next machine will minimize the gap with HL-LHC, also:***
  - As we gain knowledge, how do we prioritize the Higgs measurements?
  - Which energy to target ?
    - top-Yukawa, HH, extended Higgs sector with more generic Yukawa coupling scenarios will require > 500 GeV
    - LC approach is to start at 250 GeV and then ~500 GeV - is it enough?
      - ***Which measurement are to be prioritized after the 250 GeV run***?
    - How relevant is to have polarized beams?

Which collider?

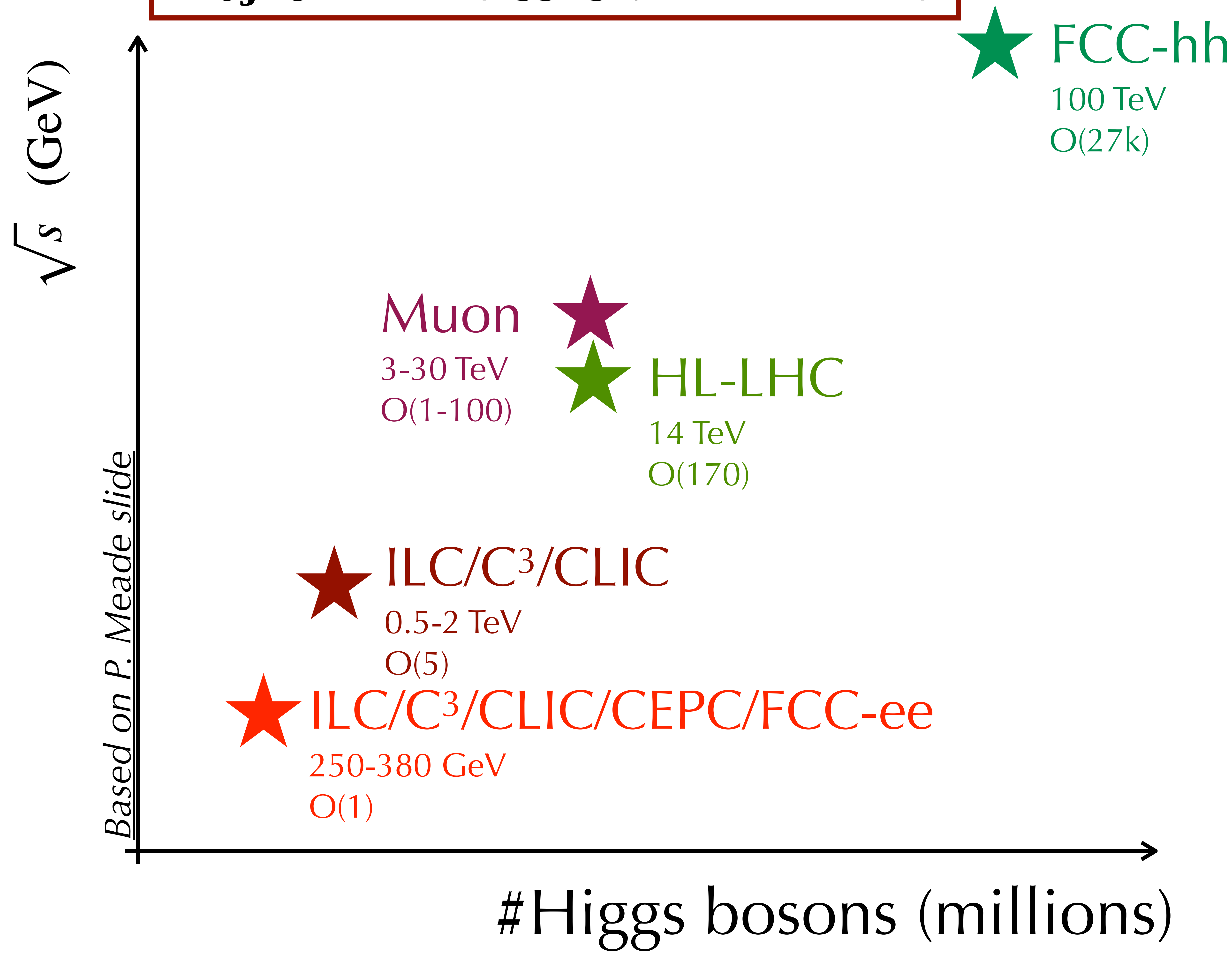
LEPTON COLLIDERS

- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C^3)
  - **250 GeV — > 1 TeV**
  - *Reach higher energies, and can use polarized beams*
- **μ+μ-**
  - **3-30 TeV**

HADRON COLLIDERS

- **75-200 TeV** (FCC-hh)

PROJECT READINESS IS VERY DIFFERENT

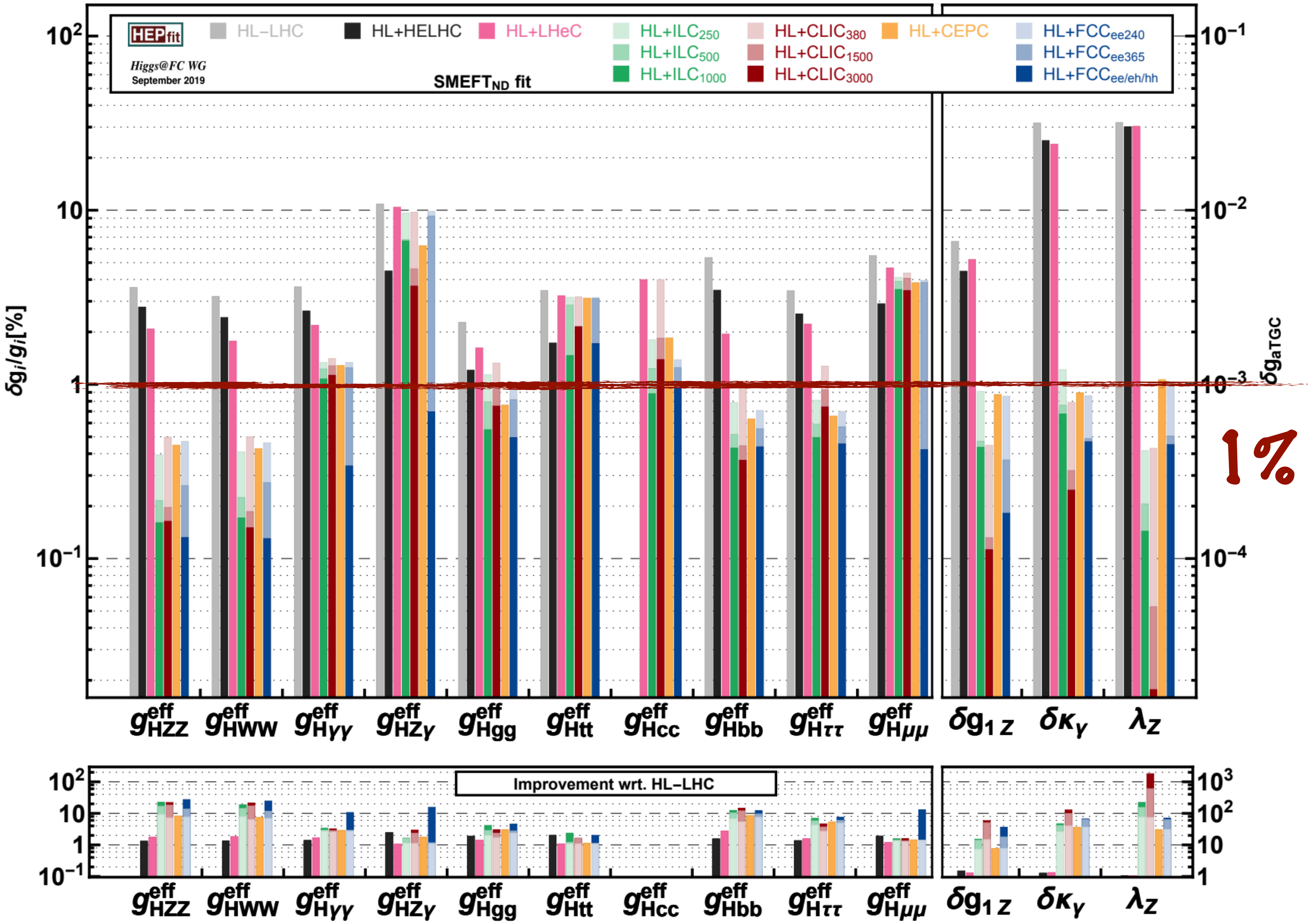


Based on P. Meade slide

arXiv:1910.11775,arXiv:1905.03764
CERN-LPCC-2018-04

Higgs couplings at future colliders

- Future colliders under consideration will improve with respect to the HL-LHC the understanding of the Higgs boson couplings - 1-5%
  - **Coupling to charm** quark could be measured with an accuracy of ~1% in future e+e- machines
  - **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC
  - At low energy top-Higgs coupling is not accessible at future lepton colliders



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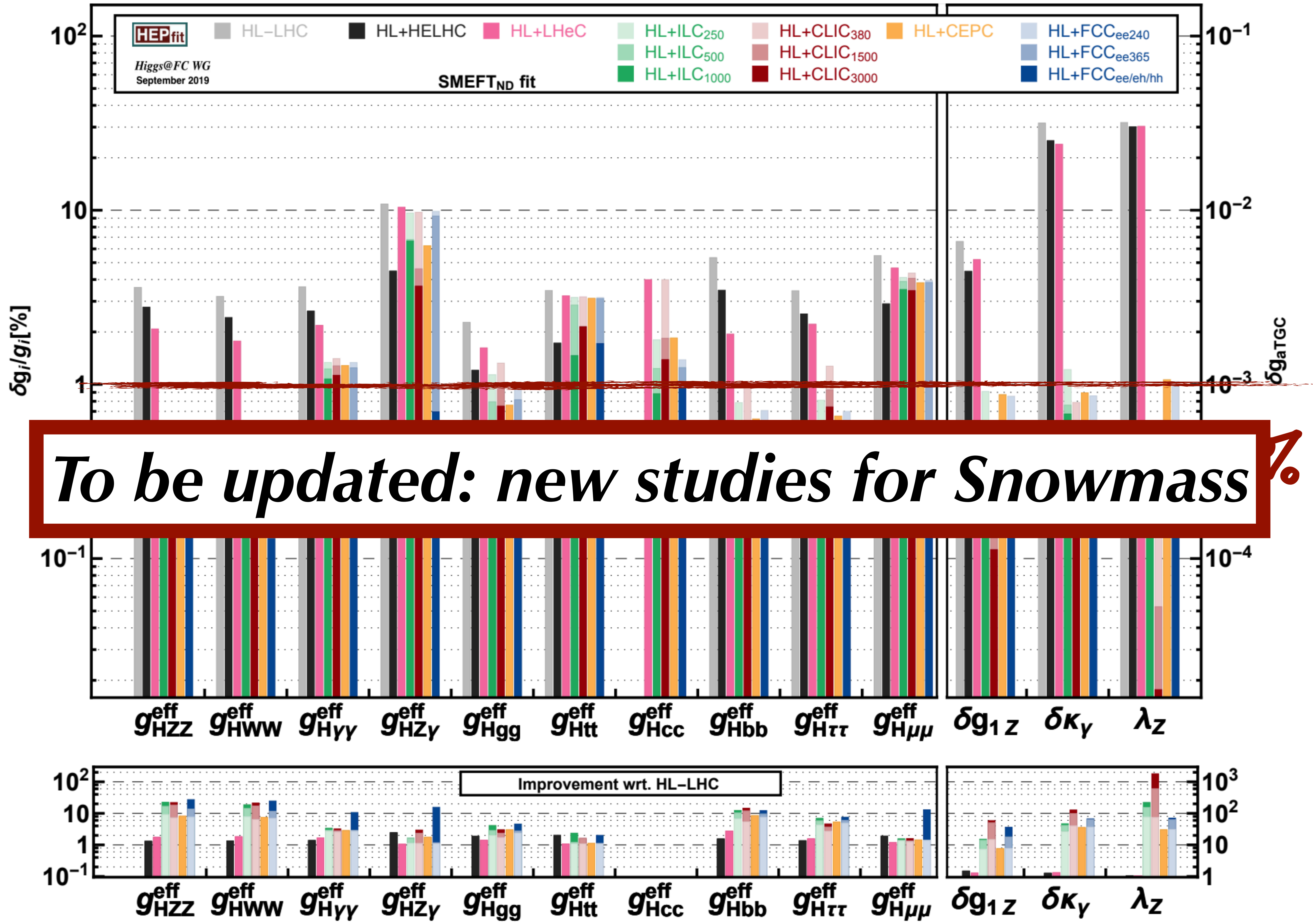


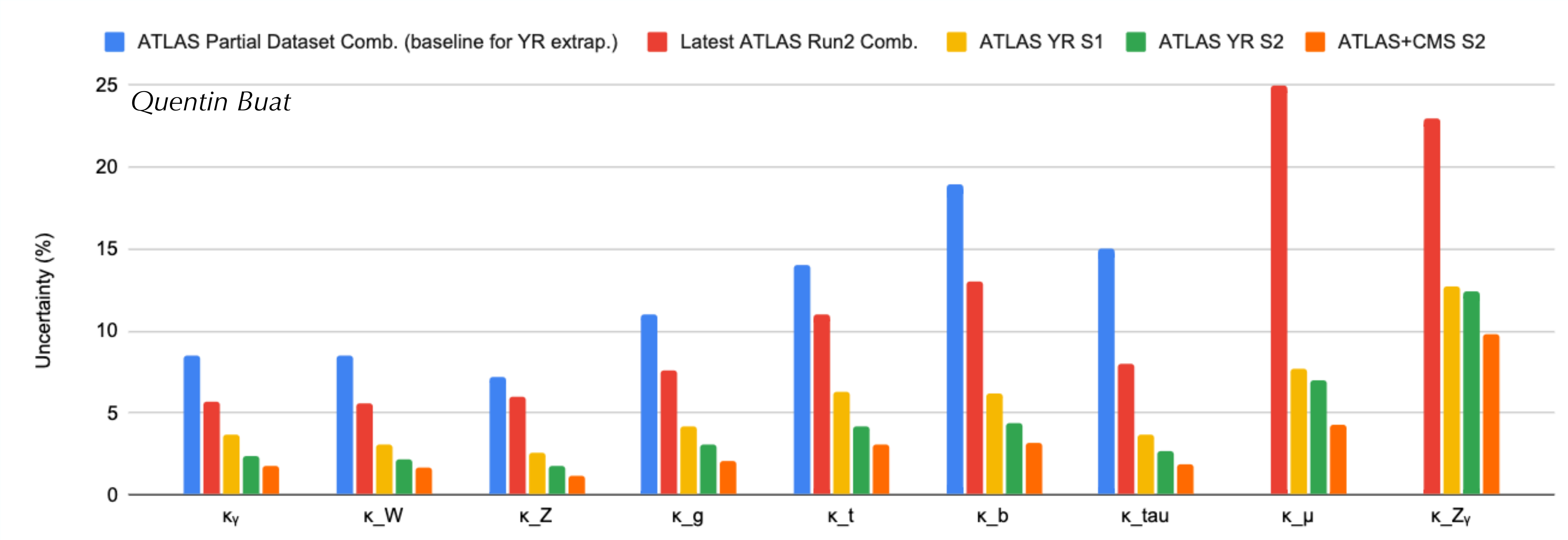
To be updated: new studies for Snowmass

New for Snowmass

- 17+5 submissions to EF01/2
- ATLAS+CMS HL-LHC : a new baseline to compare the next machine to
  - Higgs to **μ/γ**, self-coupling and differential measurements particularly relevant for the complementarity with e+e-
- H to ss at e+e-
- **Electron** Yukawa at circular e+e-
- CP studies at e+e-
- Higgs invisible e+e-
- Updated projections at muon collider

New from HL-LHC

ATLAS+CMS HL-LHC 2022 study



YR projections based on analyses of partial Run 2 dataset

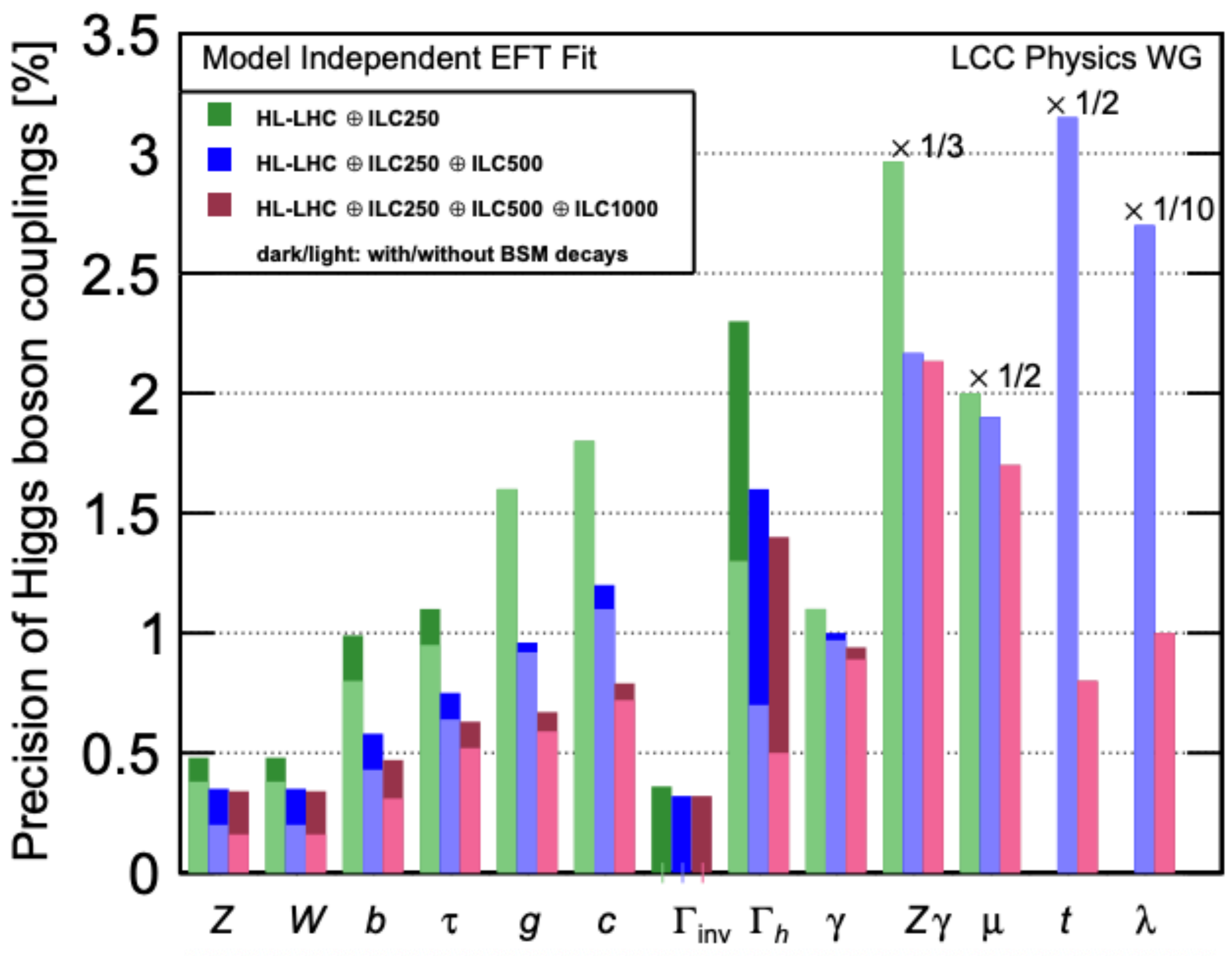
Full Run 2 measurements have drastically improved previous results

We need to update our HL-LHC projections

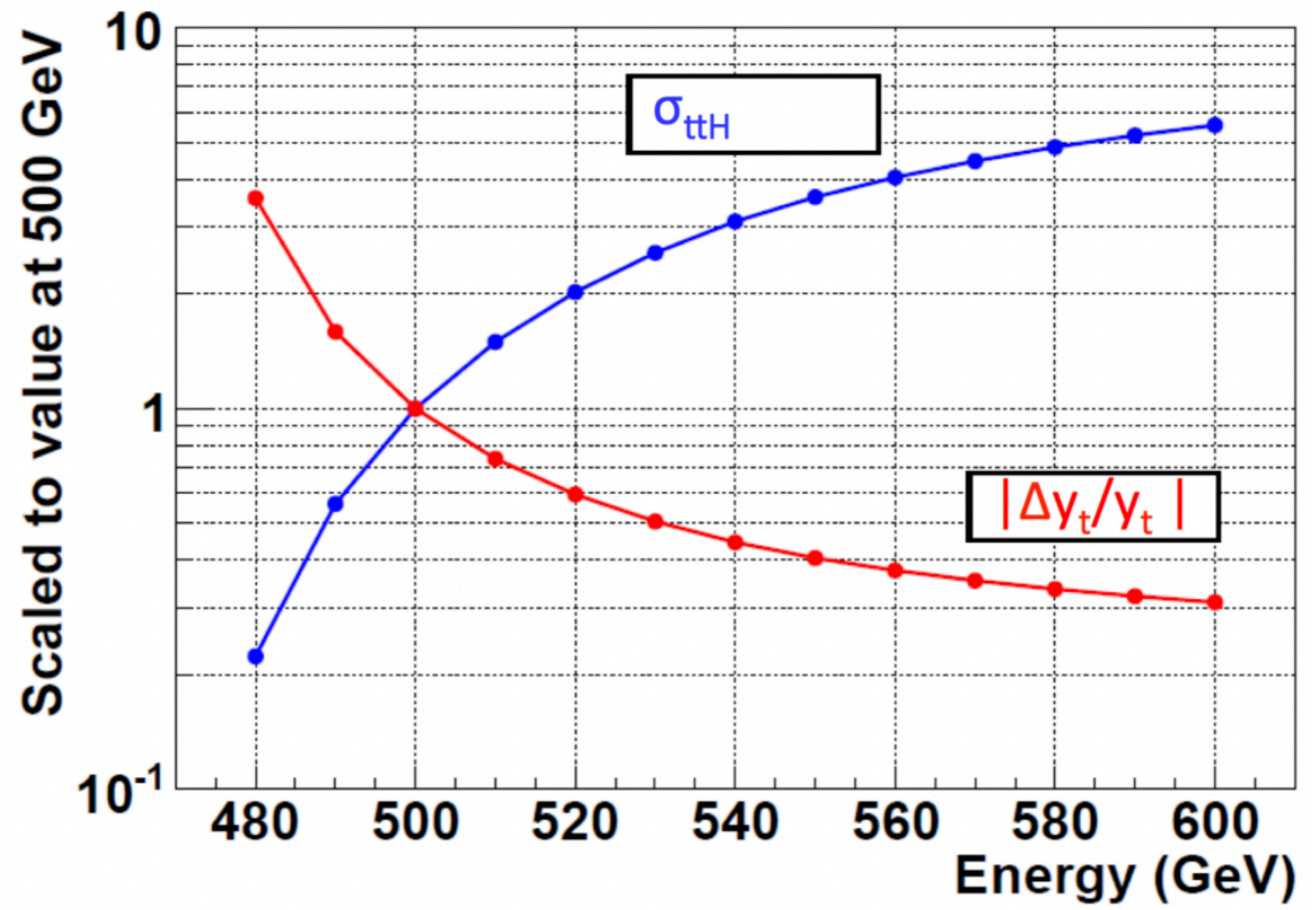
Updated Higgs couplings for ILC

arXiv:2203.07622
arXiv:1908.11299
arXiv:1506.07830

coupling	ILC250 full	ILC250 no BSM	ILC500 full	ILC500 no BSM	ILC1000 full	ILC1000 no BSM
hZZ	0.49	0.38	0.35	0.20	0.34	0.16
hWW	0.48	0.38	0.35	0.20	0.34	0.16
hbb	0.99	0.80	0.58	0.43	0.47	0.31
$h\tau\tau$	1.1	0.95	0.75	0.63	0.63	0.52
hgg	1.6	1.6	0.96	0.91	0.67	0.59
hcc	1.8	1.7	1.2	1.1	0.79	0.72
$h\gamma\gamma$	1.1	1.0	1.0	0.96	0.94	0.89
$h\gamma Z$	8.9	8.9	6.5	6.5	6.4	6.4
$h\mu\mu$	4.0	4.0	3.8	3.7	3.4	3.4
htt	—	—	6.3	6.3	1.0	1.0
hhh	—	—	20	20	10	10
Γ_{tot}	2.3	1.3	1.6	0.70	1.4	0.50
Γ_{inv}	0.36	—	0.32	—	0.32	—



Note C³ would run at 550 GeV, a factor 2 improvement to the top-Yukawa coupling (*)



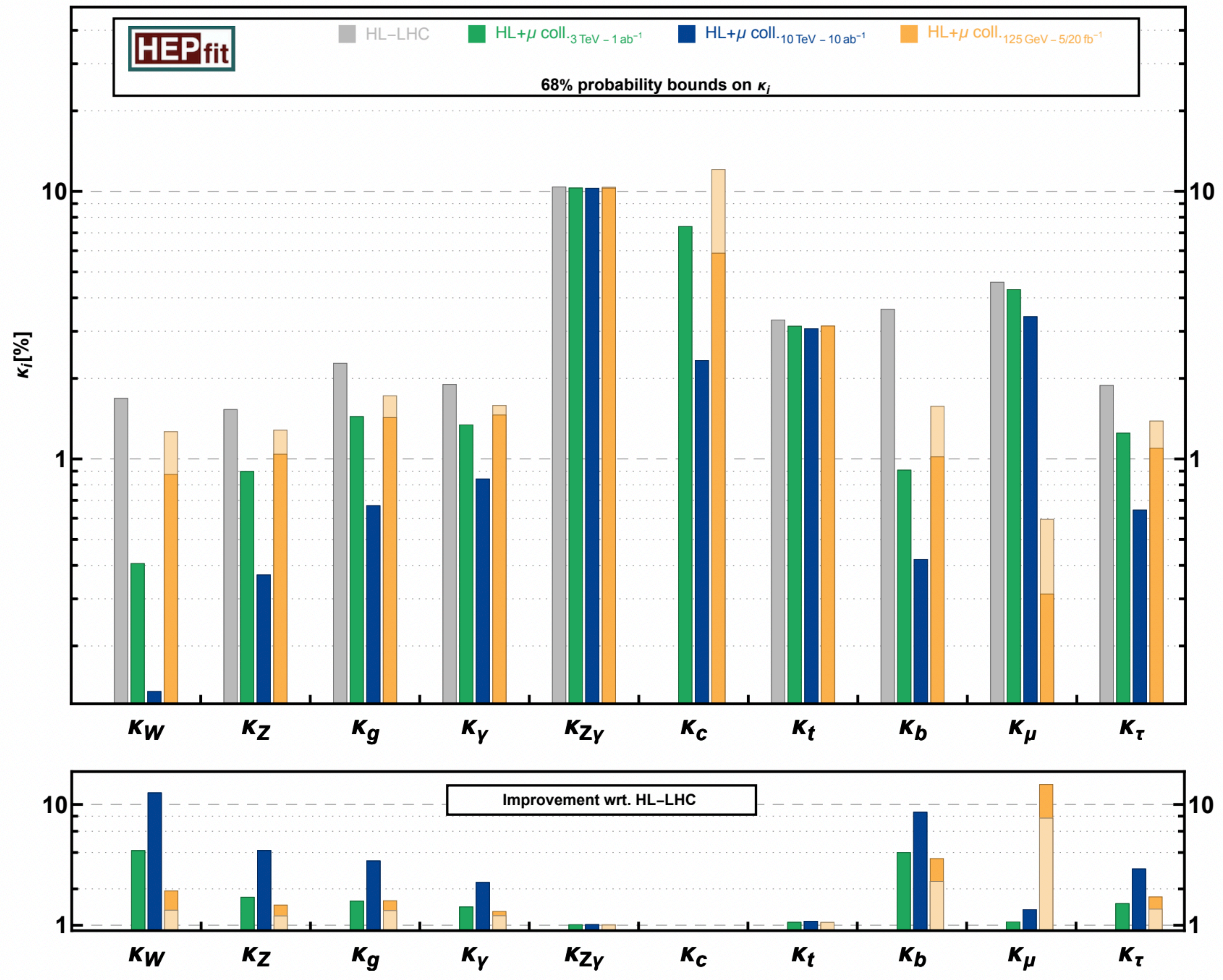
One note on polarization

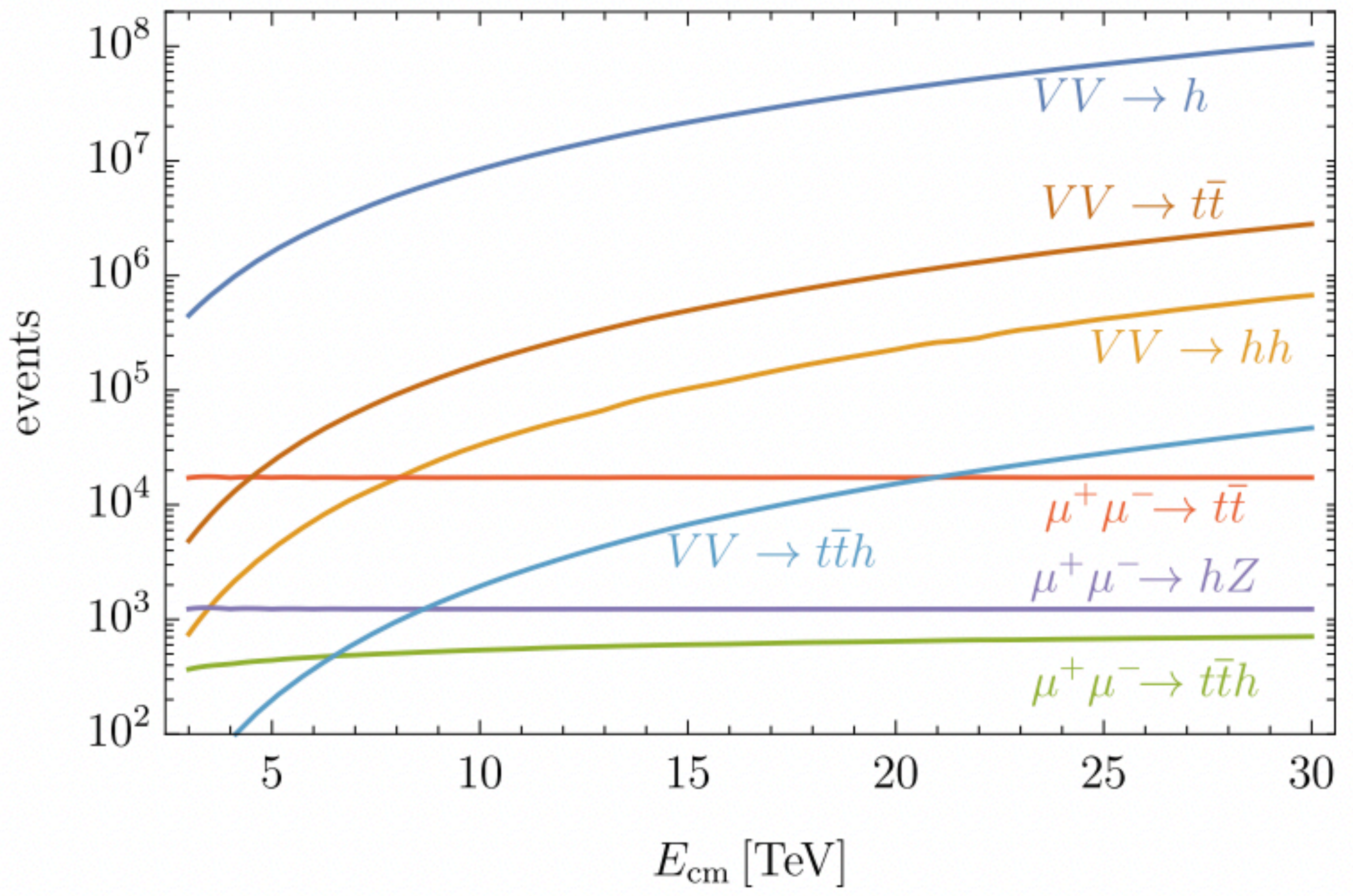
- There are extensive comparisons between the FCC-ee plan and the C3/ILC runs that show they are rather **compatible to study the Higgs Boson**
- When analyzing Higgs couplings with SMEFT, 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.
  - **Electron polarization is essential** for this
  - There is almost no difference in the expectation with and without **positron polarization**.
    - more cross-checks of systematic errors.
    - relevant at high energy (> TeV) where the most important cross sections are initiated from $e^-_L e^+_R$

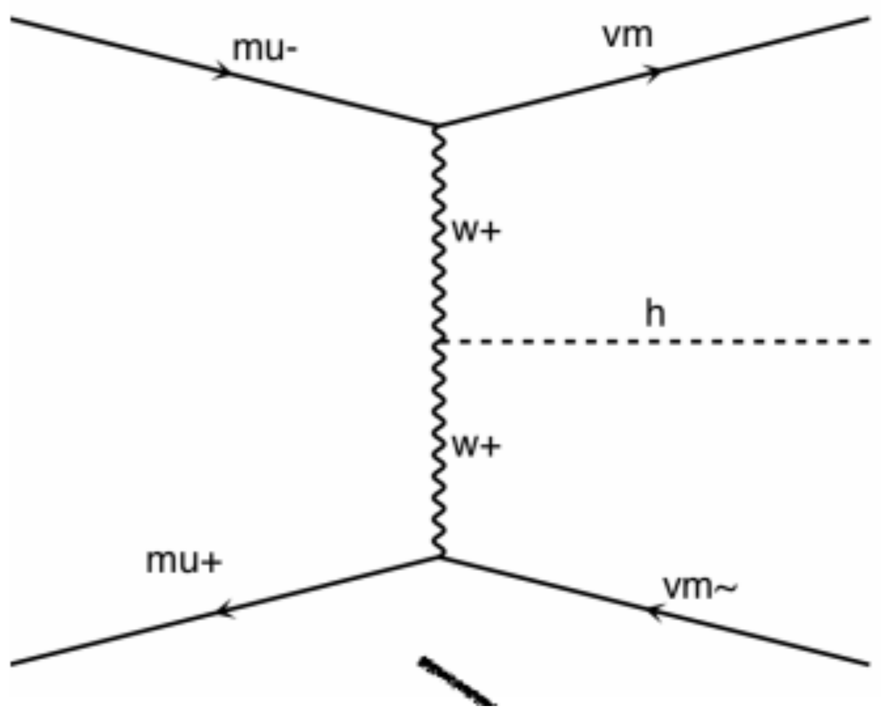
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

arXiv:2203.07261

Higgs couplings at the muon collider





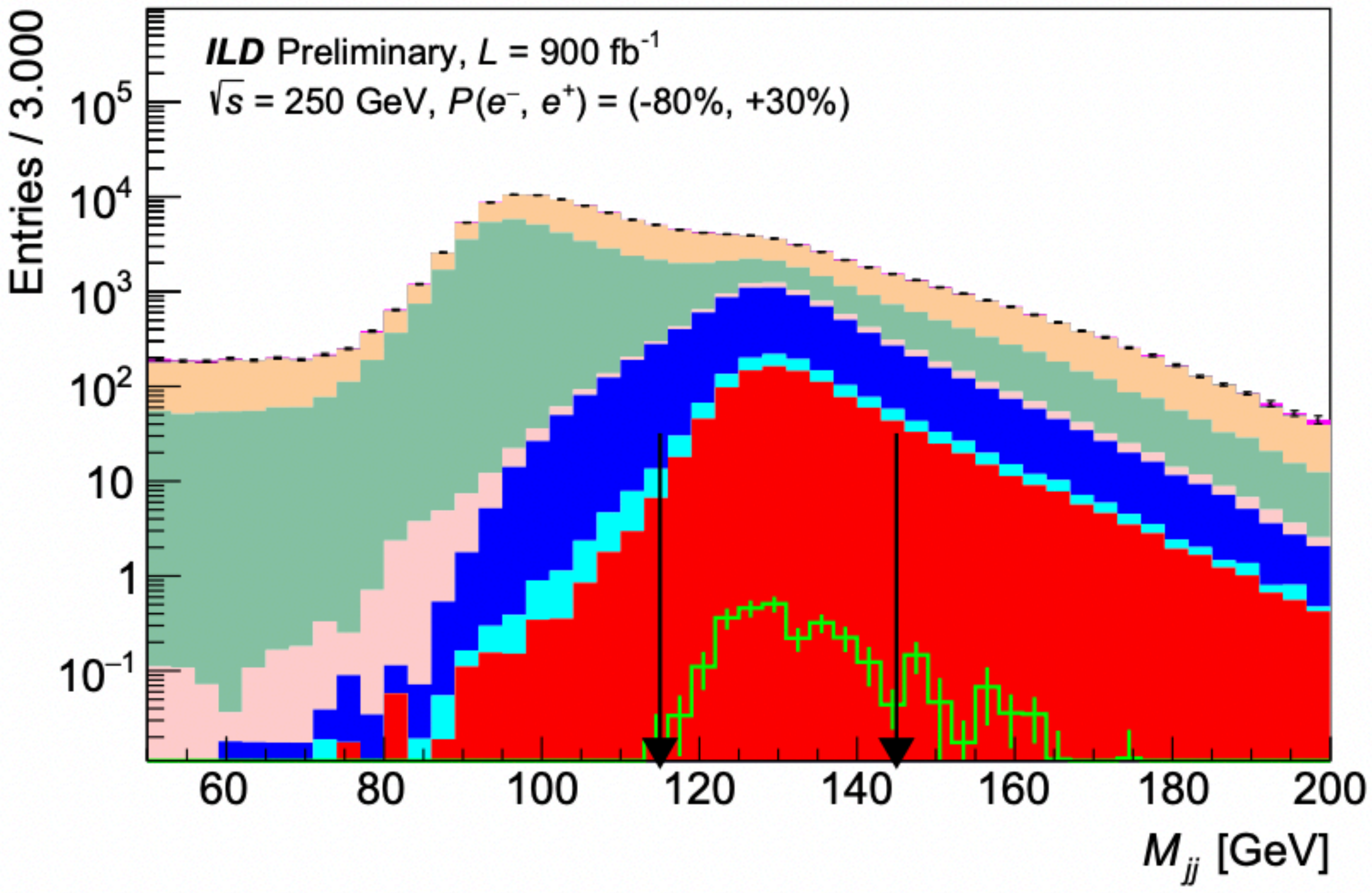


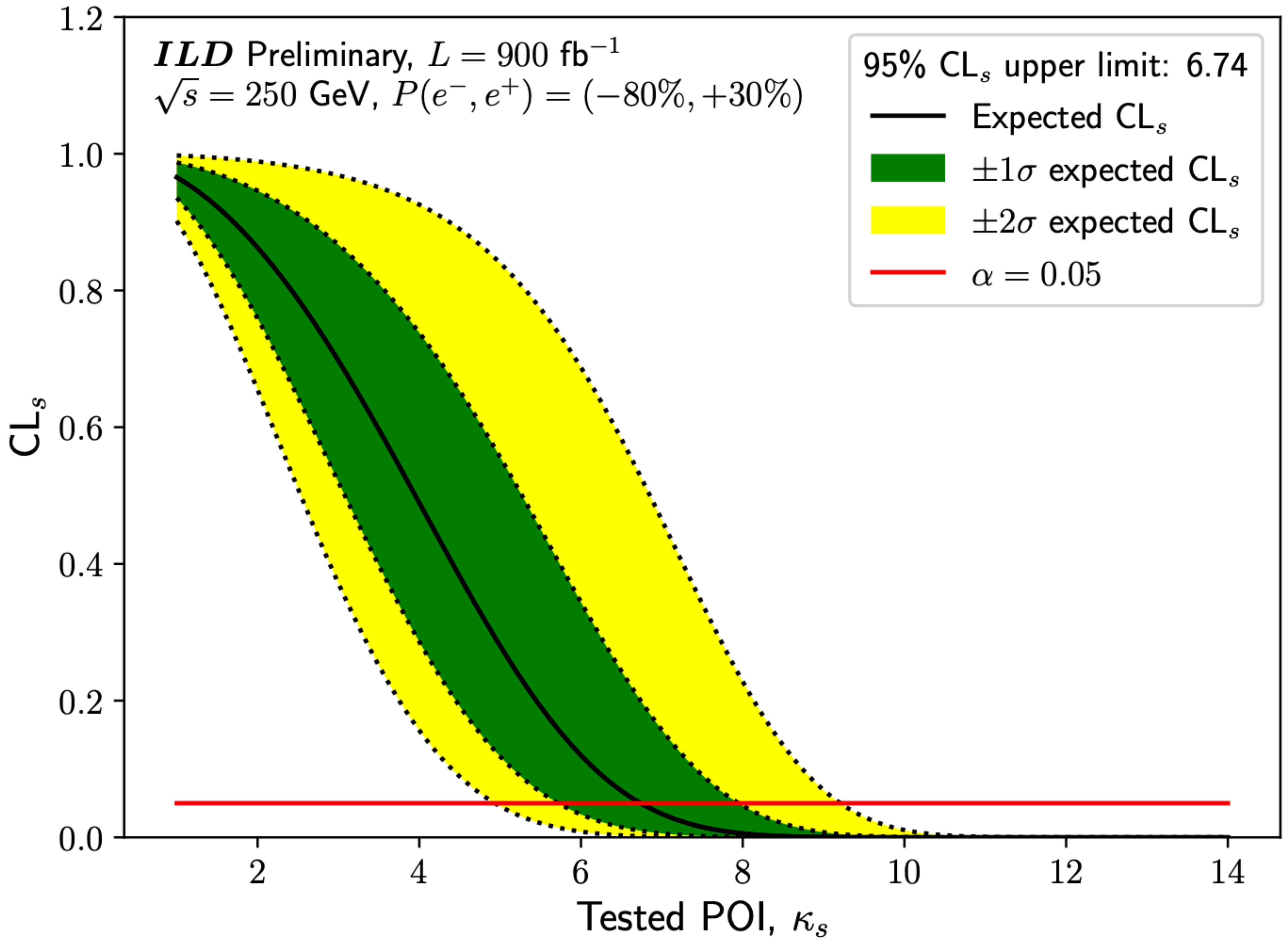
H to strange coupling

arXiv:2203.07535

- Exploring ZH with Z going to leptons or neutrinos
- Combined limit of κs < 6.74 at 95% CL with 900/fb at 250 GeV (i.e. half dataset)

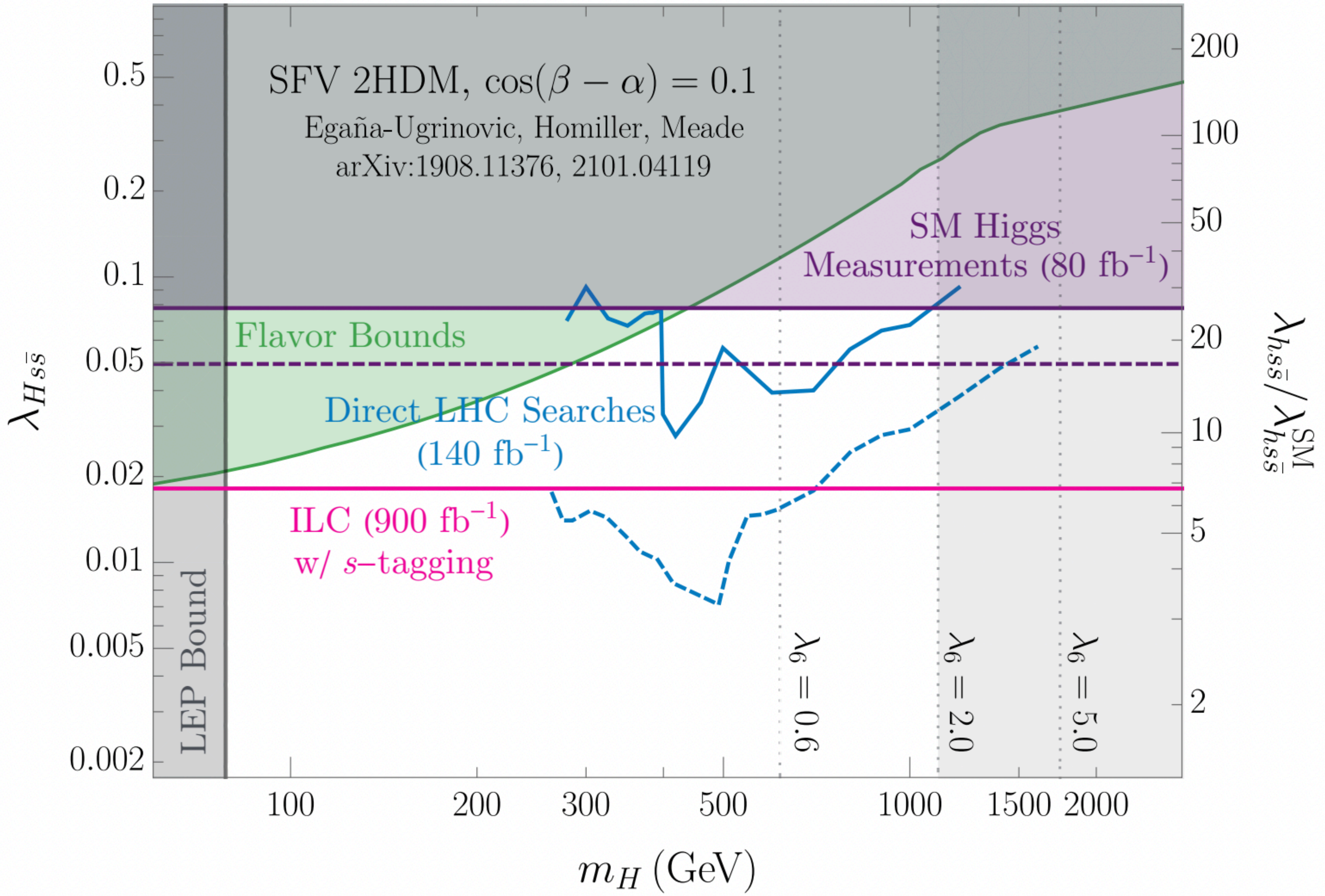
NEW!





BSM interpretation?

arXiv:2203.07535



Extending the sensitivity beyond LHC to 2HDM

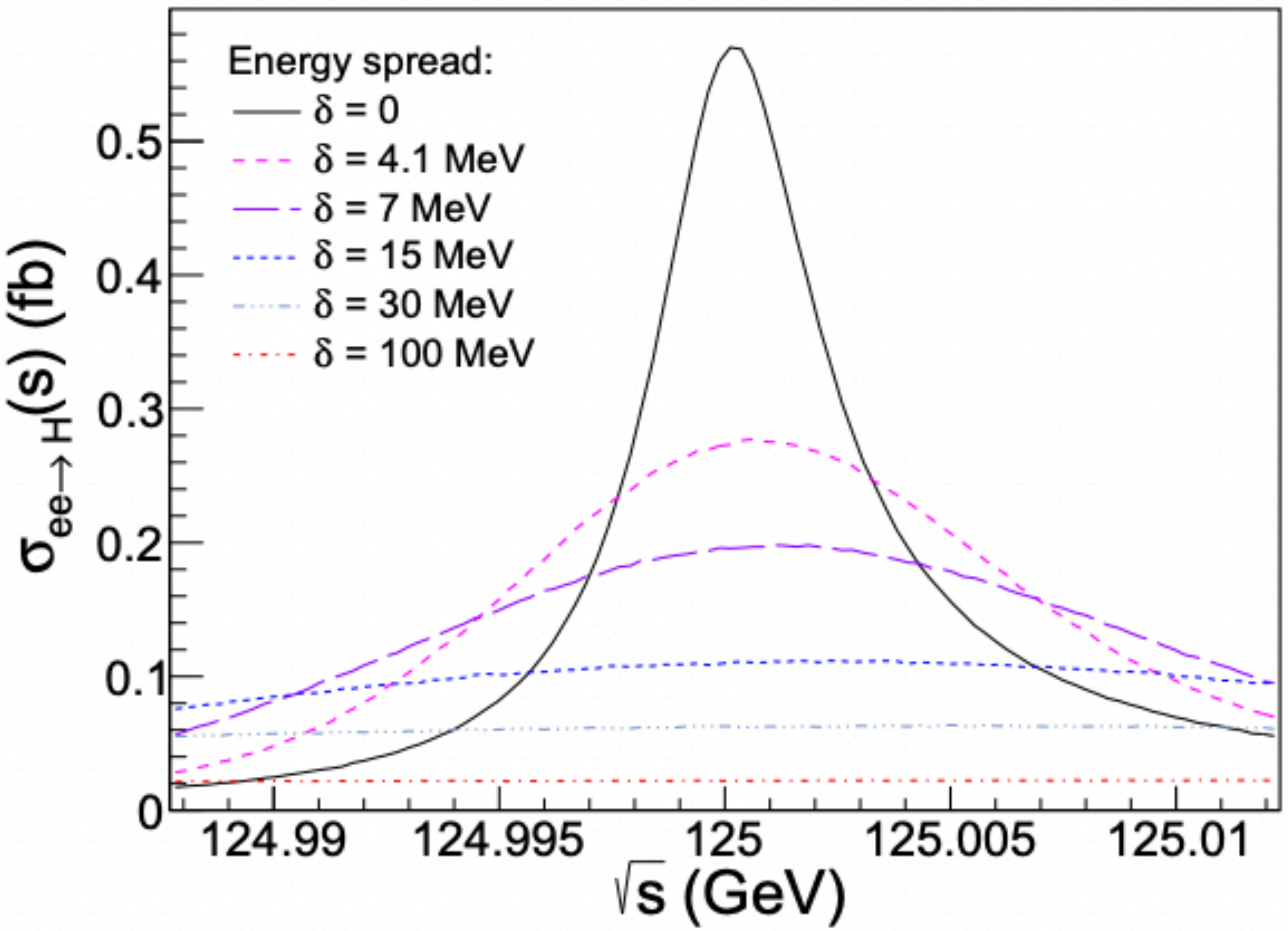
A spontaneous flavour violating (SFV) 2HDM allows for large couplings of additional Higgs to strange/light quarks while suppressing flavour-changing neutral currents

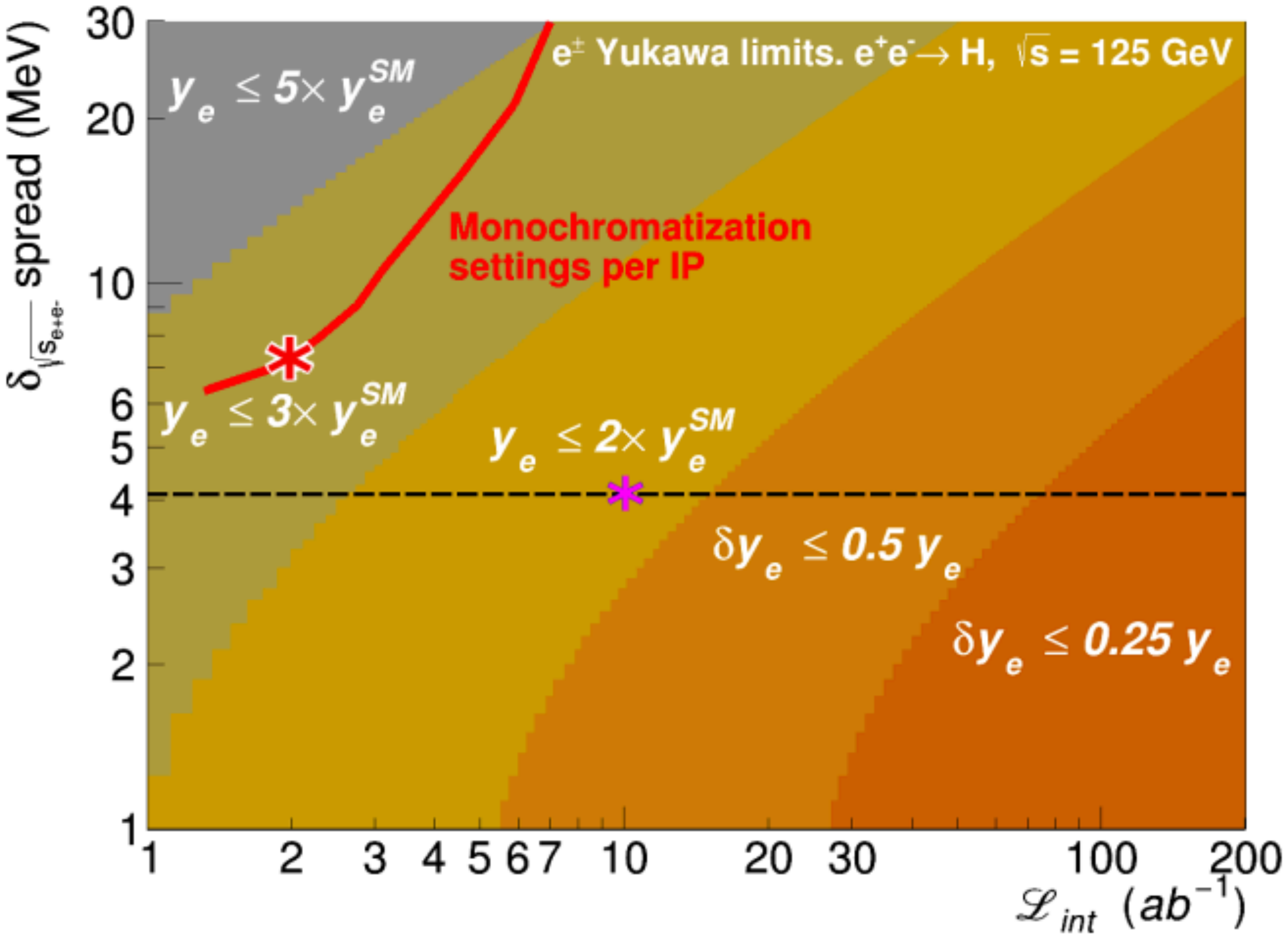
Higgs-electron Yukawa

arxiv:2107.02686

- **Electron** Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass
  - $\kappa_e < 1.6$ at 95% CL

NEW!





CP properties

- Goal is to sharpen theoretical expectations / models (see summary from Andrei Gritsan)
  - Connect to broader EFT and distinguish between linear and quadratic effects in the observables
- CP measurement using the **τ Yukawa coupling** at e+e- at 250 GeV with a precision of 75 mrad
  - Higher energy stages, at a TeV or higher, can be used to measure CP effects in the HZZ coupling by studying the ZZ-fusion Higgs production process (to be followed up)
- **Higgs-top CP-structure** via the tth production at the HL-LHC, FCC-hh and muon colliders.

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$\lvert\alpha\rvert \lesssim 36°$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 25°$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 3°$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}
$\lvert\alpha\rvert \lesssim 9°$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\lvert\alpha\rvert \lesssim 3°$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

The Higgs Boson potential

- At the present time, we have no experimental evidence that the Higgs boson results from the scalar potential of the SM
  - Observing double Higgs Boson production is crucial
- **Precision measurements of double Higgs** boson production can then be combined **with single Higgs** measurements for a better understanding of the structure of the Higgs potential.
- Models of **new physics that contain multiple Higgs bosons** can lead to the production of Higgs bosons with different masses, leading to new experimental signatures
  - We have discussed a possible set of **benchmarks for HH resonant** interpretations:
    - Based on additional Singlet and 2HDM
    - Either that would be accessible at e+e- or higher energy collider and still not excluded by HL-LHC
    - Considerations about EWPT

The Higgs self-coupling at future colliders

- CMS & ATLAS projections have been updated
  - New combination can be done ?
- New since the YR, **FCC-hh** : 2.9-5.5% depending on the systematic assumptions (arXiv:2004.03505)
- **Muon collider** 25% (6%) at 3 (10) TeV

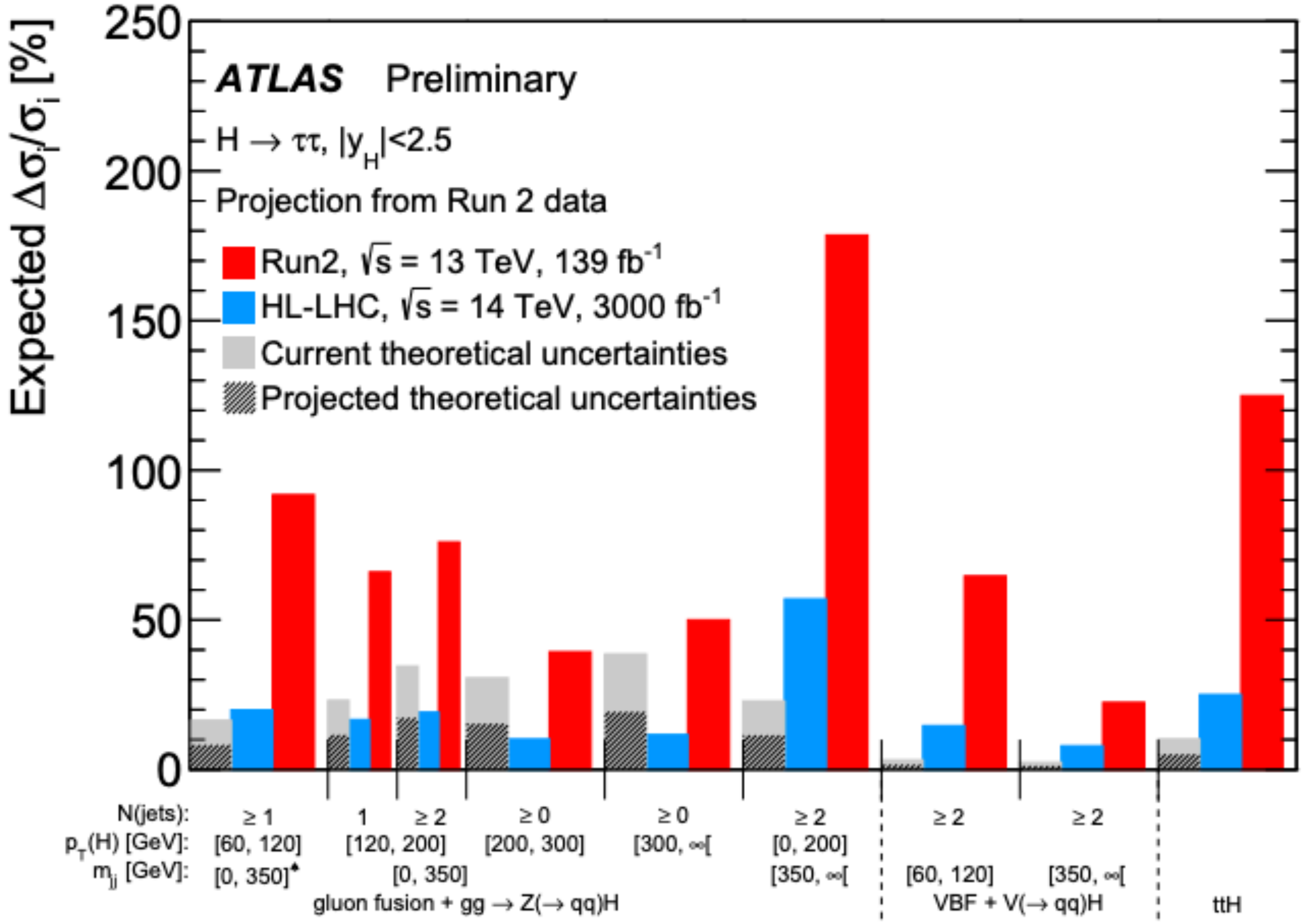
	3 TeV μ-coll. L$\approx$ 1 ab^{-1}	10 TeV μ-coll. L= 10 ab^{-1}	14 TeV μ-coll. L$\approx$ 20 ab^{-1}	30 TeV μ-coll. L= 90 ab^{-1}
	68% prob. interval			
$\delta\kappa_\lambda$	[-0.27,0.35] $\cup$ [0.85,0.94] $\rightarrow$[-0.15,0.16] (2$\times$ L)	[-0.035, 0.037]	[-0.024, 0.025]	[-0.011, 0.012]

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
CEPC$_{240}$	49%	–	49%
C^3 ILC$_{250}$	49%	–	49%
C^3 ILC$_{500}$	38%	27%	22%
ILC$_{1000}$	36%	10%	10%
CLIC$_{380}$	50%	–	50%
CLIC$_{1500}$	49%	36%	29%
CLIC$_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
* FCC-hh	-	5%	5%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

Higgs production at large p_T

- European Strategy Studies focused on inclusive measurements : **new opportunities for measurements of the Higgs couplings at large Q^2**
  - BSM effects often grow with energy
  - Clear impact on the extraction of EFT constraints via correlations among different processes and kinematical regimes
  - Also this helps mitigating systematic uncertainties and maximizes the robustness of the results
    - i.e. pile-up rejection and trigger capabilities
- Few **examples**:
  - VH at large invariant mass (double differential distributions sometime needed to restore BSM/SM interference)
    - Probing the HWW coupling at high Q^2 in pp→WH at large mass or in VBF is complementary to measure BR(H→WW)
  - off-shell gg → H* → ZZ → 4l
  - Higgs + high-p_T jet

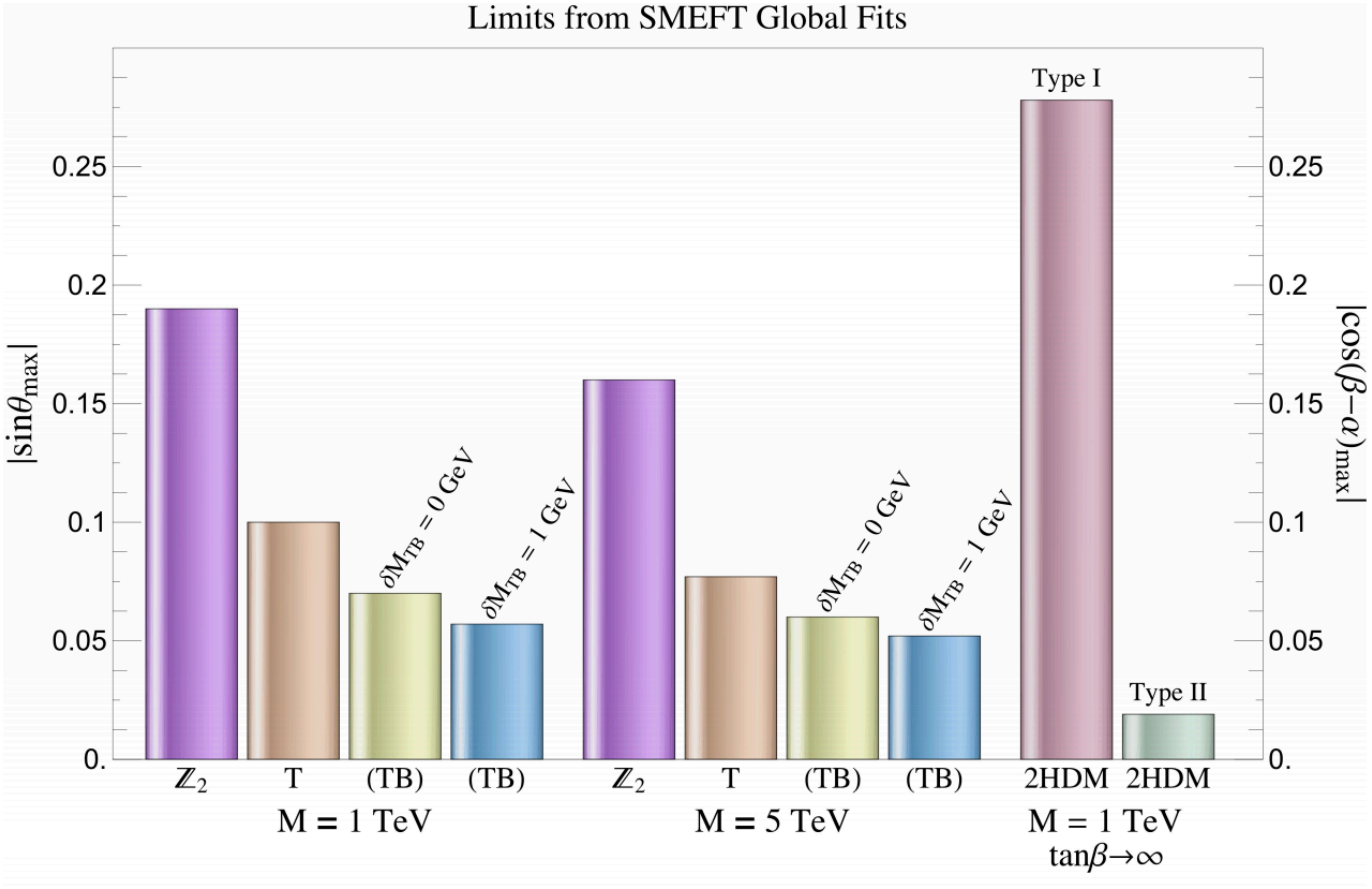


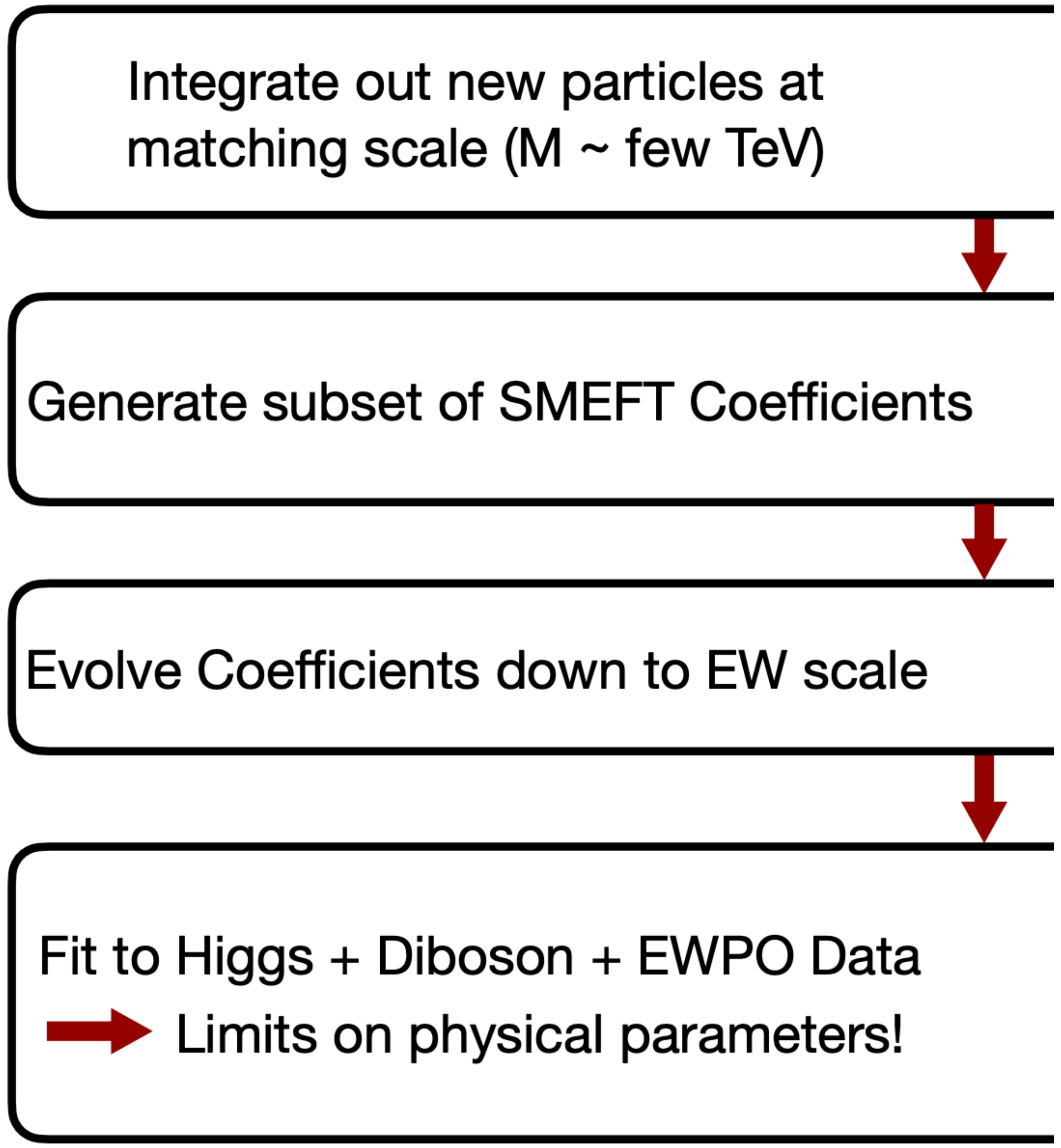
Update in VH to bb and H to $\tau\tau$

The inverse problem

arXiv:2007.01296

- Progress on how to map BSM models to SMEFT constraints
    - Include complete 1-loop matching for other models, more NLO effects in fits, and more distributions





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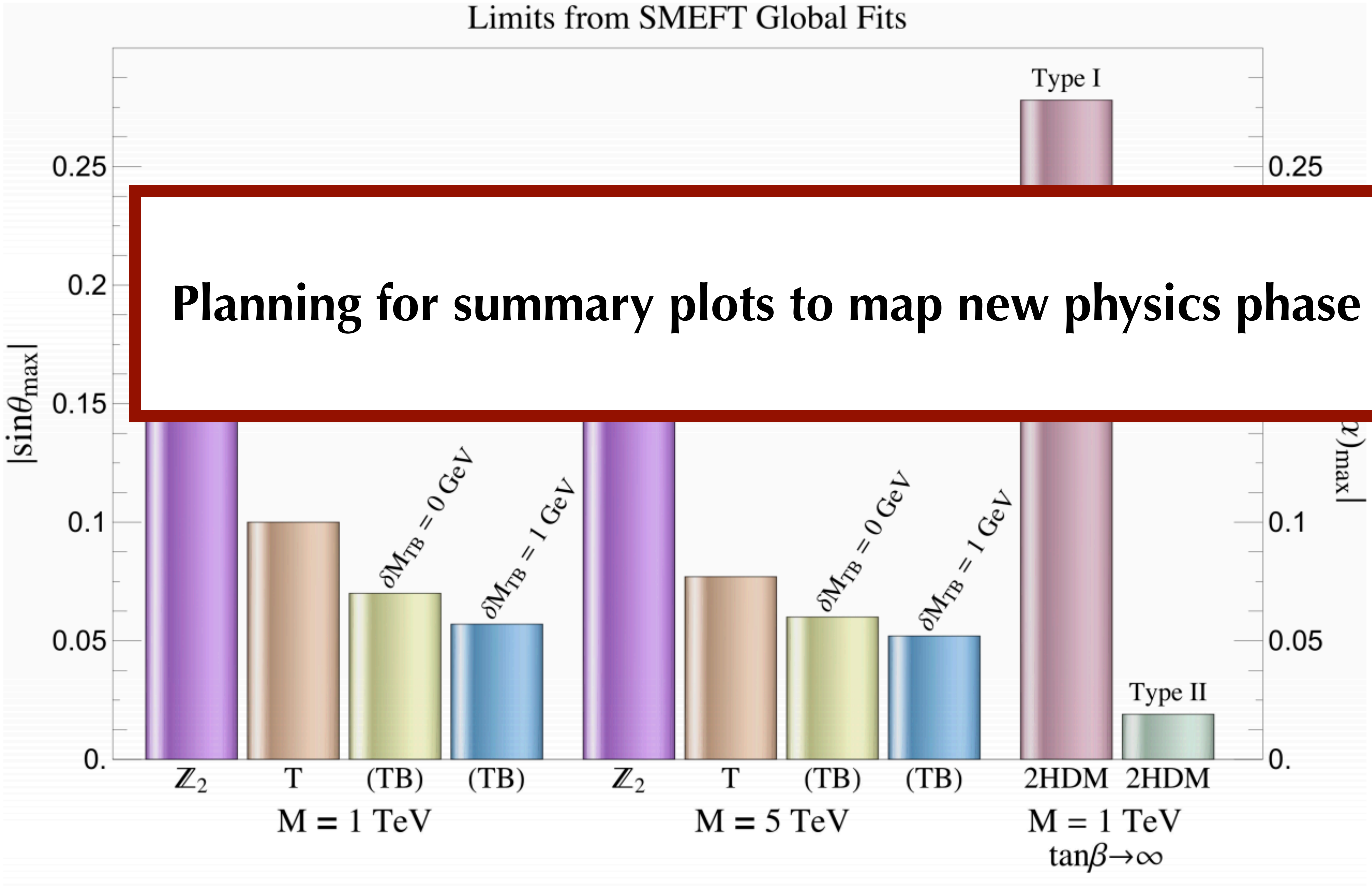
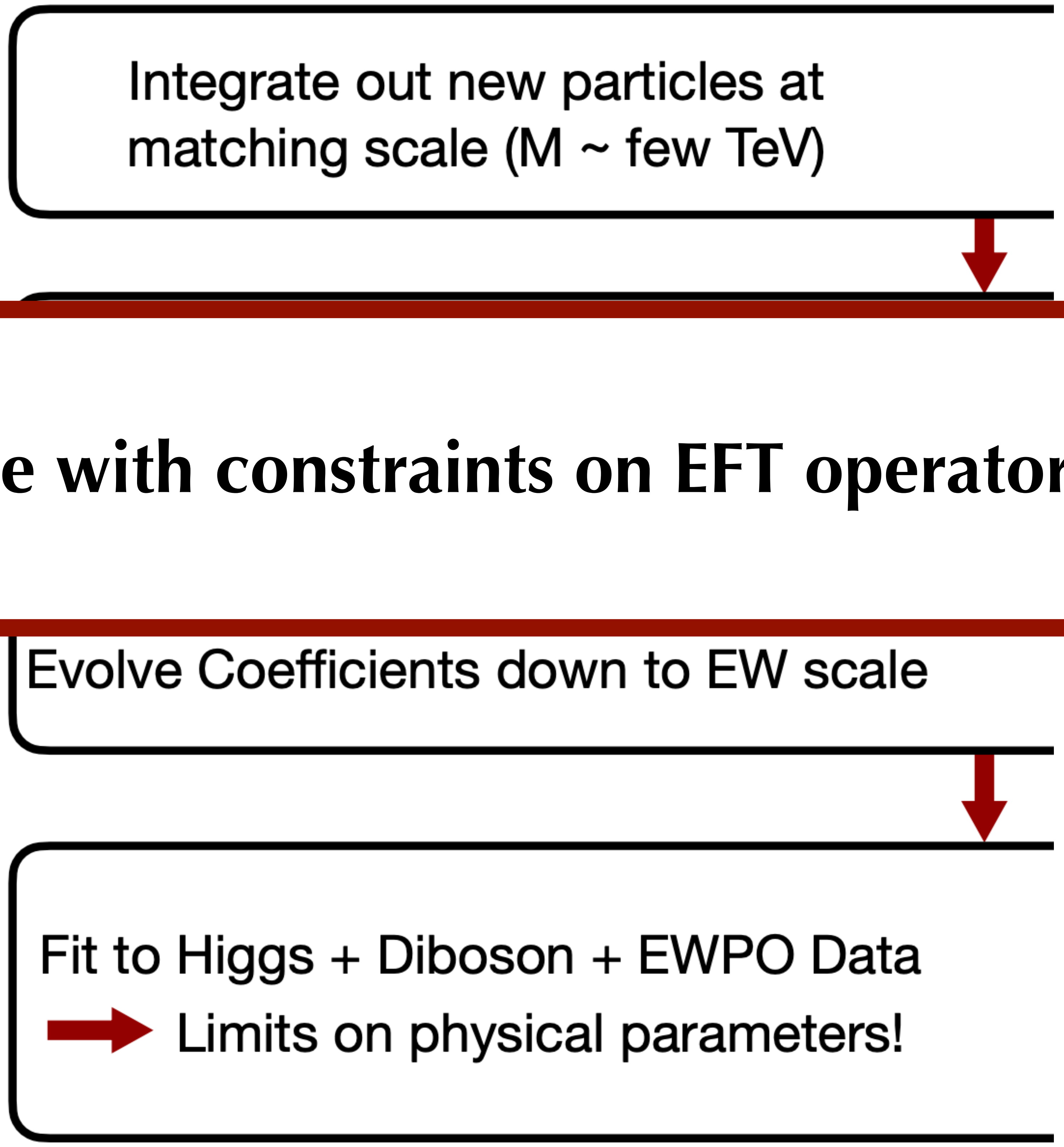


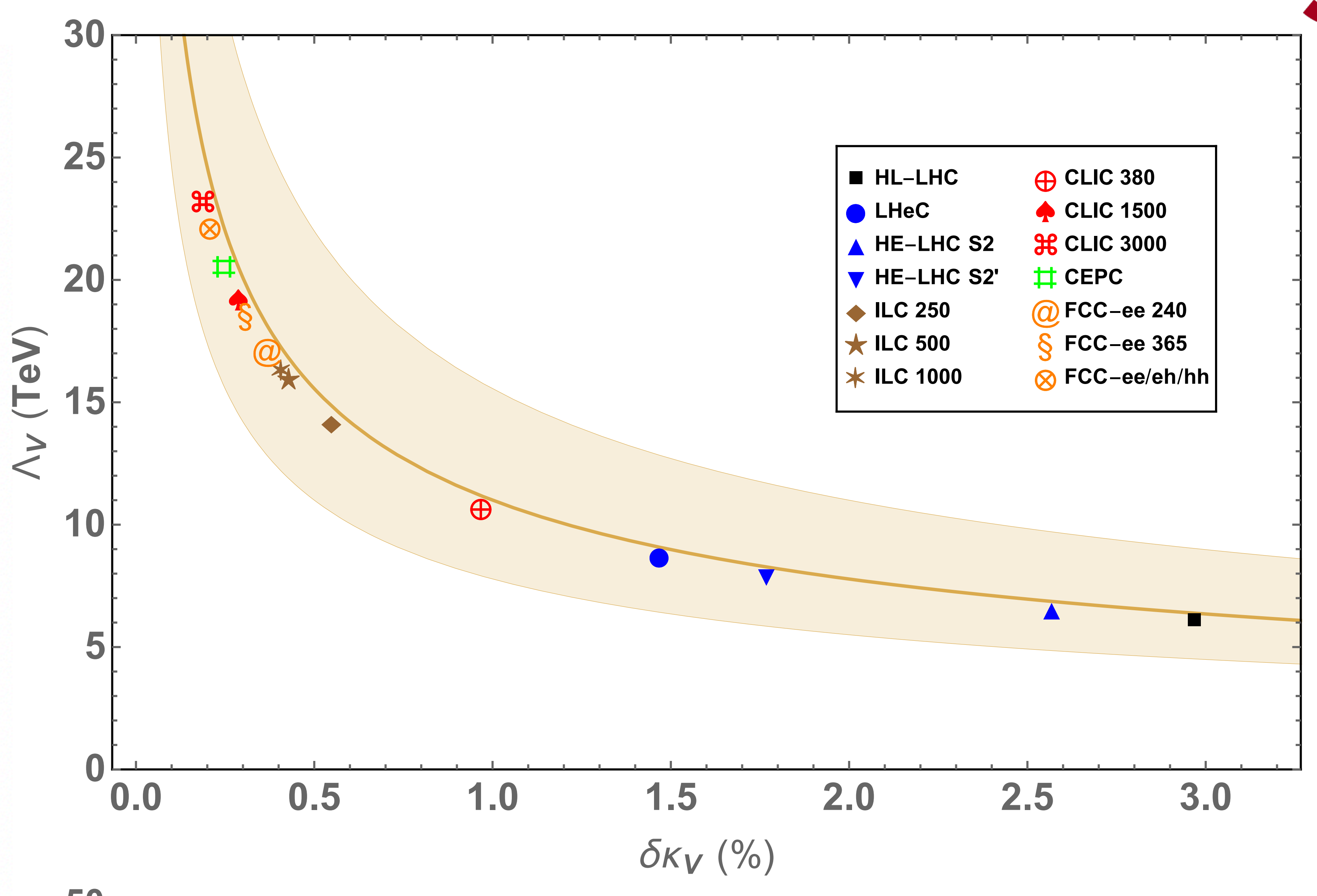


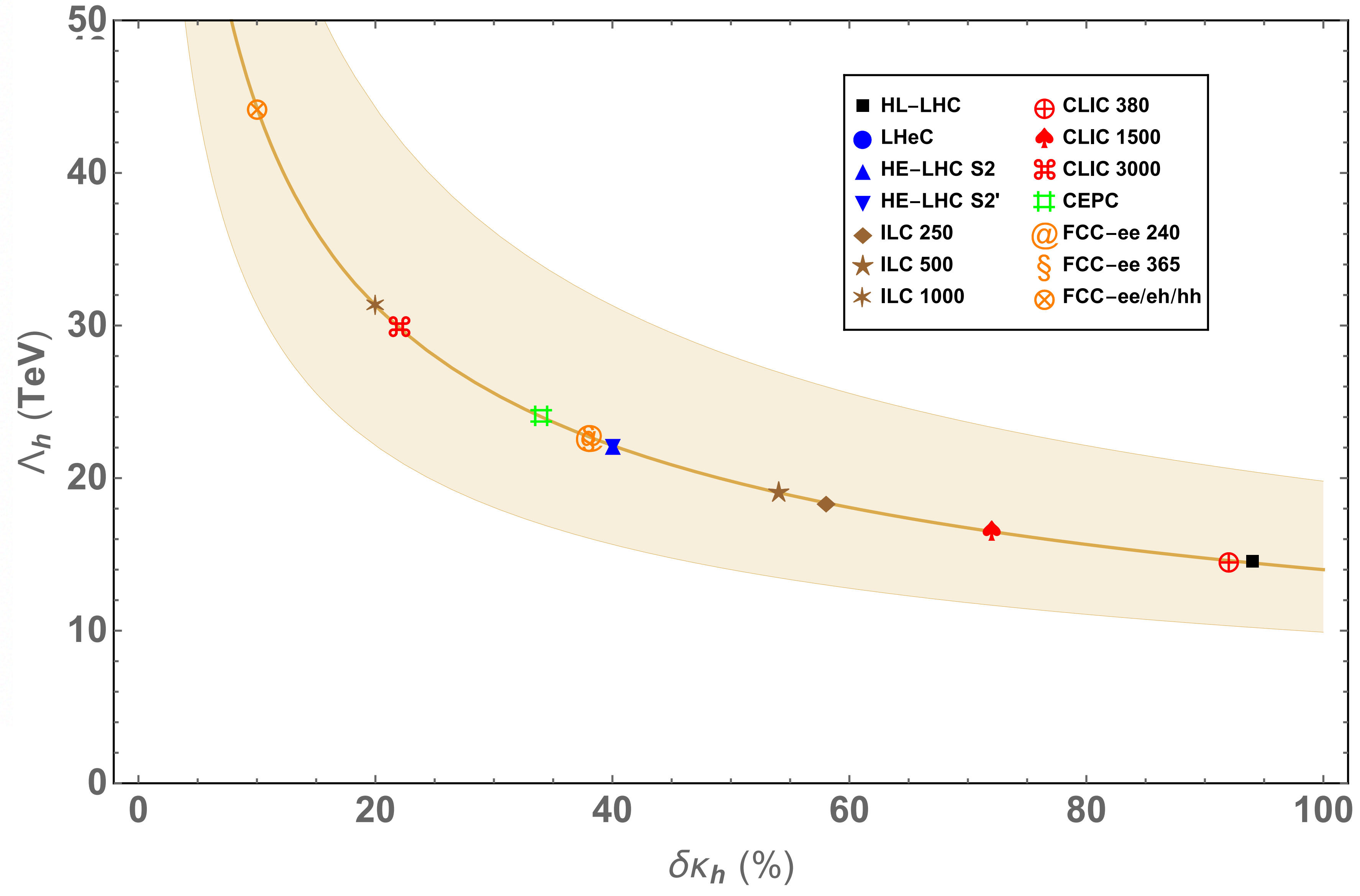
Planning for summary plots to map new physics phase space with constraints on EFT operators

Model independent bounds on new physics

arXiv:2203.09512

Coupling (2σ)	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC
Unitarity Bound			S2	S2′	250	500	1000	380	1500	3000		240	365	ee/eh/hh
$2\delta\kappa_V$ [%]	3.0	1.5	2.6	1.8	0.58	0.46	0.44	1.0	0.32	0.22	0.28	0.40	0.34	0.24
Λ_V (TeV)	6.0	9	6.4	7.7	14	15	16	10	18	22	20	16	18	21
$2\kappa_g$ [%]	4.6	7.2	3.8	2.4	4.6	1.94	1.32	5.0	2.6	1.8	3.0	3.4	2.0	0.98
Λ_g (TeV)	51	41	56	70	51	78	95	49	68	81	63	59	77	110
$2\kappa_\gamma$ [%]	3.8	15.2	3.2	2.4	13.4	6.8	3.8	196	10	4.4	7.4	9.4	7.8	0.58
Λ_γ (TeV)	120	61	130	150	65	92	120	17	76	110	88	78	86	310
$2\kappa_{Z\gamma}$ [%]	20	–	11.4	7.6	198	172	170	240	30	13.8	16.4	162	150	1.38
$\Lambda_{Z\gamma}$ (TeV)	34	–	45	55	11	12	12	10	28	41	37	12	12	130
$2\delta\kappa_t$ [%]	6.6	–	5.6	3.4	–	13.8	3.2	–	–	5.4	–	–	–	2.0
Λ_t (TeV)	13	–	14	18	–	9	19	–	–	14	–	–	–	24
$2\delta\kappa_b$ [%]	7.2	4.2	6.4	4.6	3.6	1.16	0.96	3.8	0.92	0.74	2.4	2.6	1.34	0.86
Λ_b (TeV)	80	100	85	100	110	200	220	110	220	250	140	130	180	230
$2\delta\kappa_\mu$ [%]	9.2	–	5.0	3.4	30	18.8	12.4	640	26	11.6	17.8	20	17.8	0.82
Λ_μ (TeV)	590	–	800	970	320	410	510	70	350	520	420	400	420	2000
$2\delta\kappa_\tau$ [%]	3.8	6.6	3.0	2.2	3.8	1.40	1.14	6.0	2.6	1.76	2.6	2.8	1.46	0.88
Λ_τ (TeV)	220	170	250	290	220	370	410	180	270	330	270	260	360	460
$2\delta\kappa_h$ [%]	94	–	40	40	58	54	20	92	72	22	34	38	38	10
Λ_h (TeV)	15	–	23	23	19	19	32	15	17	30	25	23	23	45





Going forward

EF012-whitereport

Sally Dawson Adrey Korytov Patrick Meade
Isobel Ojalvo Caterina Vernieri

March 2022

DRAFT!

1 Introduction

2 Why Higgs is great

2.1 Centrality of Higgs in SM

2.2 Questions the Higgs leaves us

2.3 Status report of what we know for sure and what's missing experimentally (self couplings, light yukawas, "unitarization")

2.4 New types of measurements vs increased precision (e.g. differential)

2.5 What BSM Higgs physics can influence

2.6 Models of BSM Higgs

Models addressing physics questions vs exploring Higgs like possibilities/property modifications

- EFT
- Higgs portal
- Singlet
- Doublet
- Higgs importance in larger frameworks?
- Naturalness, Compositeness

3 Mass, width, spin measurements

4 Update on theory calculations of Higgs rates

5 Impact of differential measurements

6 Higgs coupling measurements with emphasis on light Yukawas

7 CP violating Higgs coupling measurements

8 Update on prospects for observing HH

9 Update on new analysis techniques for Higgs physics and what they mean

10 How coupling measurements and HH impact understanding of EFTs

11 Why go beyond the SM?

12 The big motivations for BSM Higgs

13 Some models showing complementarity of direct searches and precision measurements: Singlet, 2HDM, ?

14 Targets for precision based on models

15 Detector/accelerator requirements to observe new physics

Expanding 1:
- - How do we go further, energy, luminosity, clean environment (snowmass options, connect to AF, IF)

Towards the final reports:

- **Which physics beyond the Standard Model can be probed by precision measurements of Higgs couplings?**
  - How precise do these measurements need to be in order to probe BSM physics scenarios?
  - How are direct searches for new Higgs-like particles complementary to precision Higgs coupling measurements
    - This should be studied by exploring the complementarity between HL-LHC and future colliders (*accounting for their different timelines*).
- **Does the Higgs boson result from the scalar potential of the Standard Model?**
  - How can measurements of double Higgs boson production be improved to better probe the potential ?
  - Which is the target precision for this? - *taking into account the correlations with the other Higgs measurements*
- How can measurements in the Higgs sector be combined with measurements in other sectors to improve our understanding of new physics scale?
- What theory calculations are needed to enable the theory precision to match the projected experimental precision of future measurements?

Dedicated discussion on Tuesday

Higgs & (SM?)EFT

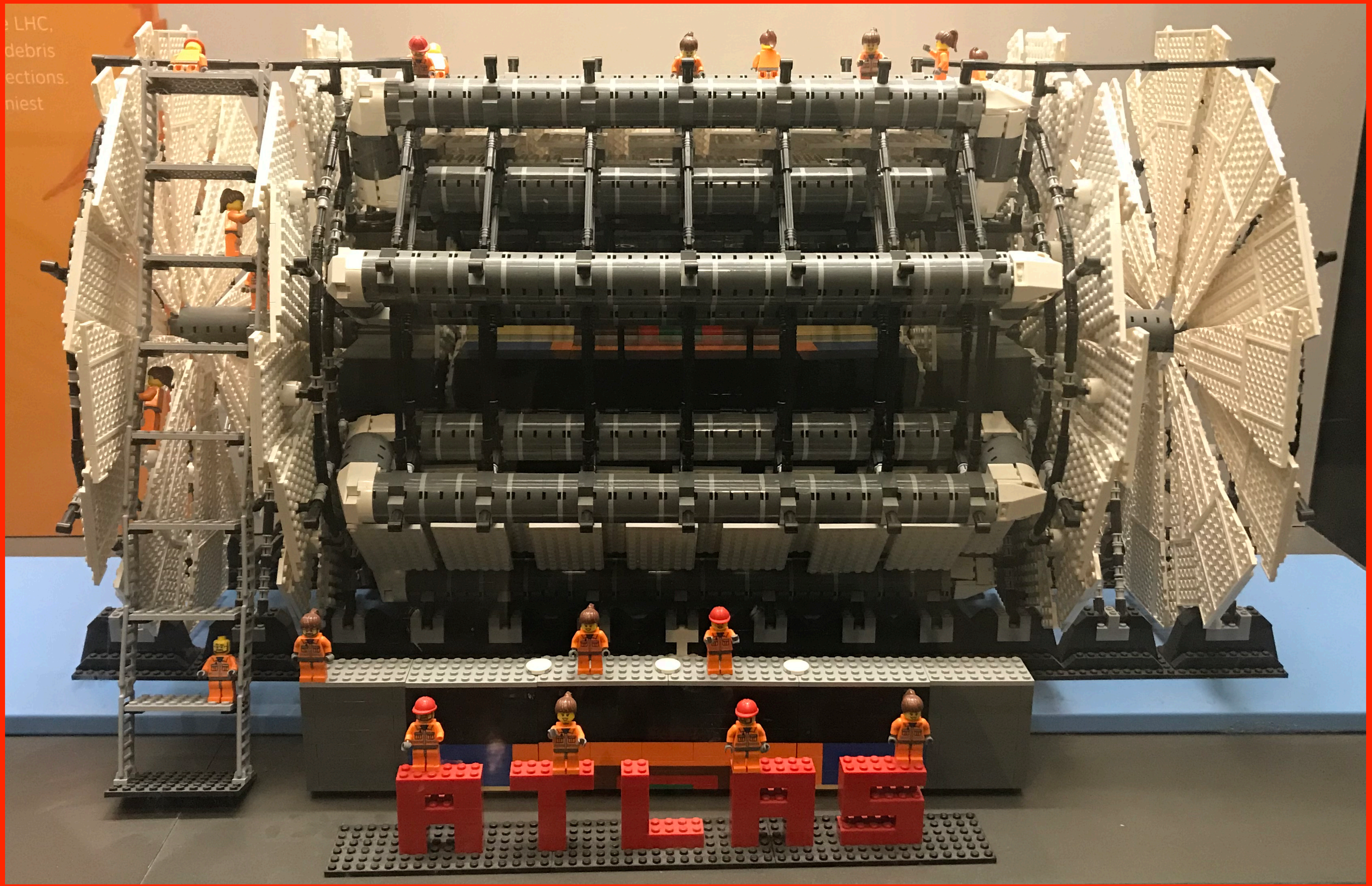
see also C. Grojean's talk

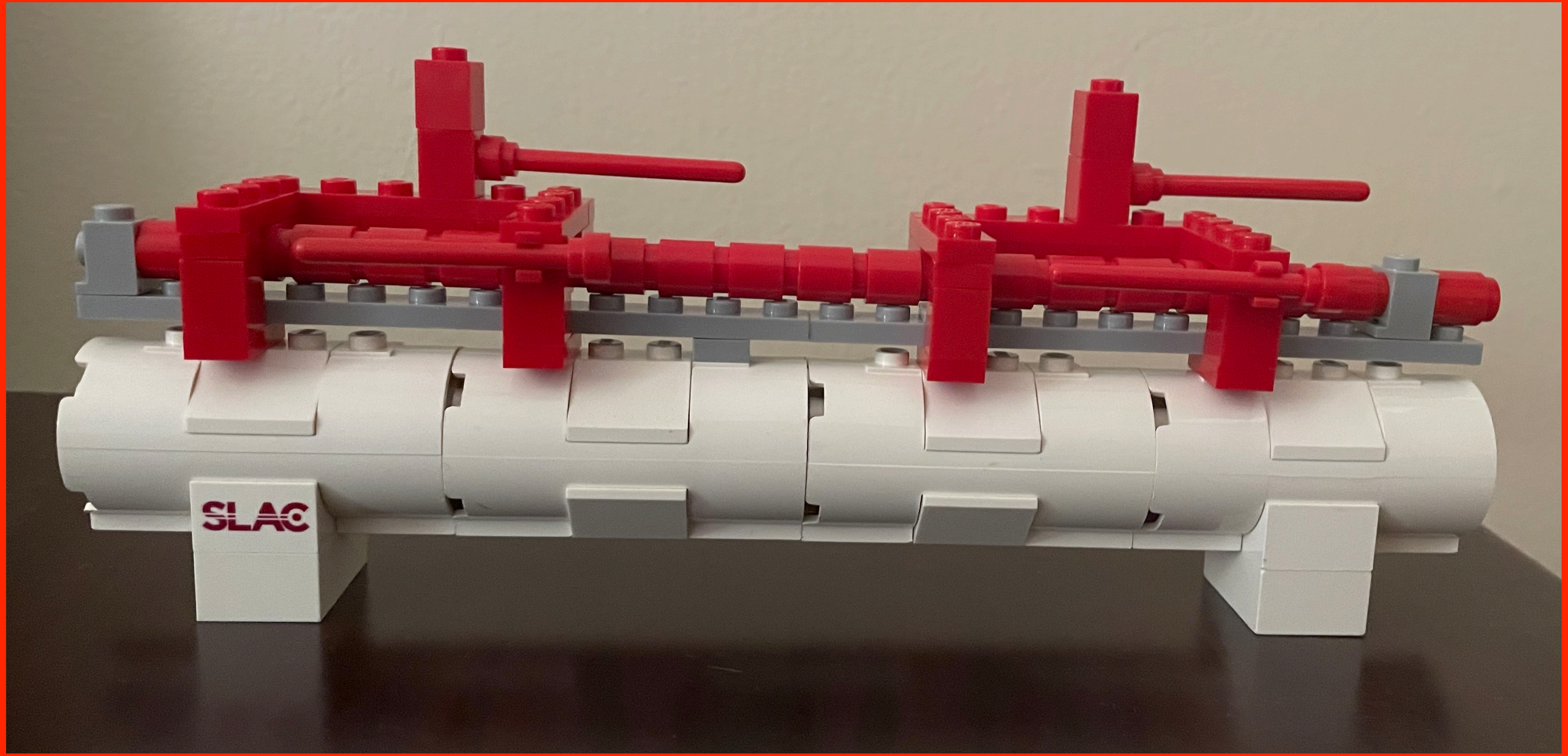
- **We will be working closely together with EF04 within the SMEFT framework:**
  - Estimate EFT uncertainties (NLO, dim-8 effects, linear vs quadratic…), new physics in backgrounds, theoretical constraints (positivity, analyticity)
  - More combined Higgs and top analysis
    1. effects of top dipoles or 4 fermion ops. with tops
    2. constraints on top EW couplings from their NLO effects in Higgs and diboson processes (particularly relevant for low-energy colliders below ttH threshold)
  - Include differential observables
  - Explore more flavor scenarios (and make connection with flavor data)
- SMEFT is a baseline, how we account for specific assumptions and model-dependency?
  - Complementarity with new physics searches

Summary plots/tables

- Higgs couplings:
  - Include updated list of machines (muon collider, C^3 are recent developments) and their parameters (including timelines)
  - Re-visit some of the assumptions (i.e. flavor..) since the ESG
  - Summary of latest theory cross sections (distributions too if available)
  - New Global fits
- Some example maps of new physics phase space to constraints on EFT operators
  - Plots that demonstrate in creative ways the BSM sensitivities of various measurements
- New physics benchmarks for resonant and non-resonant HH that we could use for interpretations as the precision on the self-coupling improves

Dedicated discussion on Wednesday





Extra

Wish list for the global fit

Inputs: Higgs @ HL-LHC

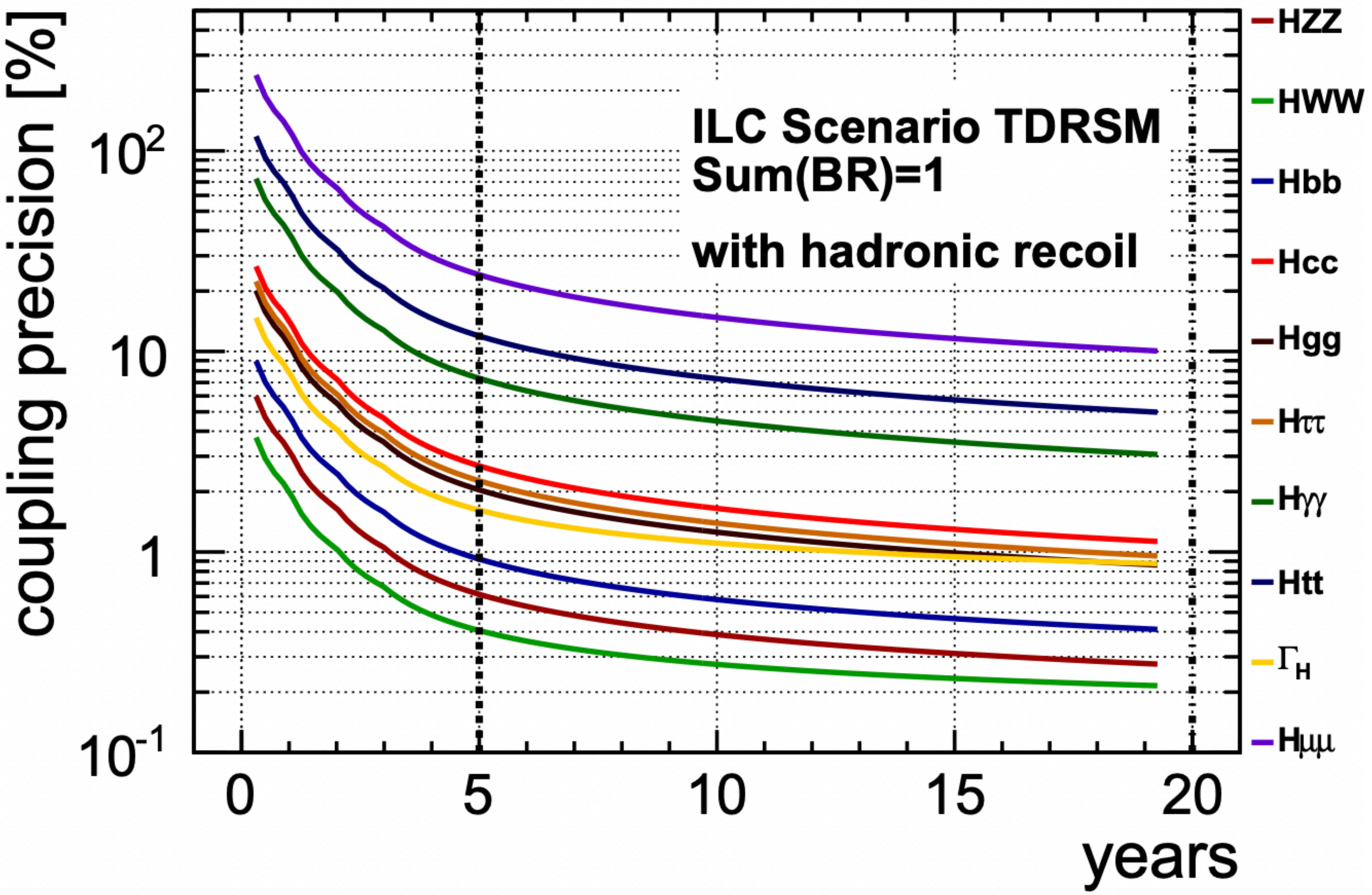
in unit of %

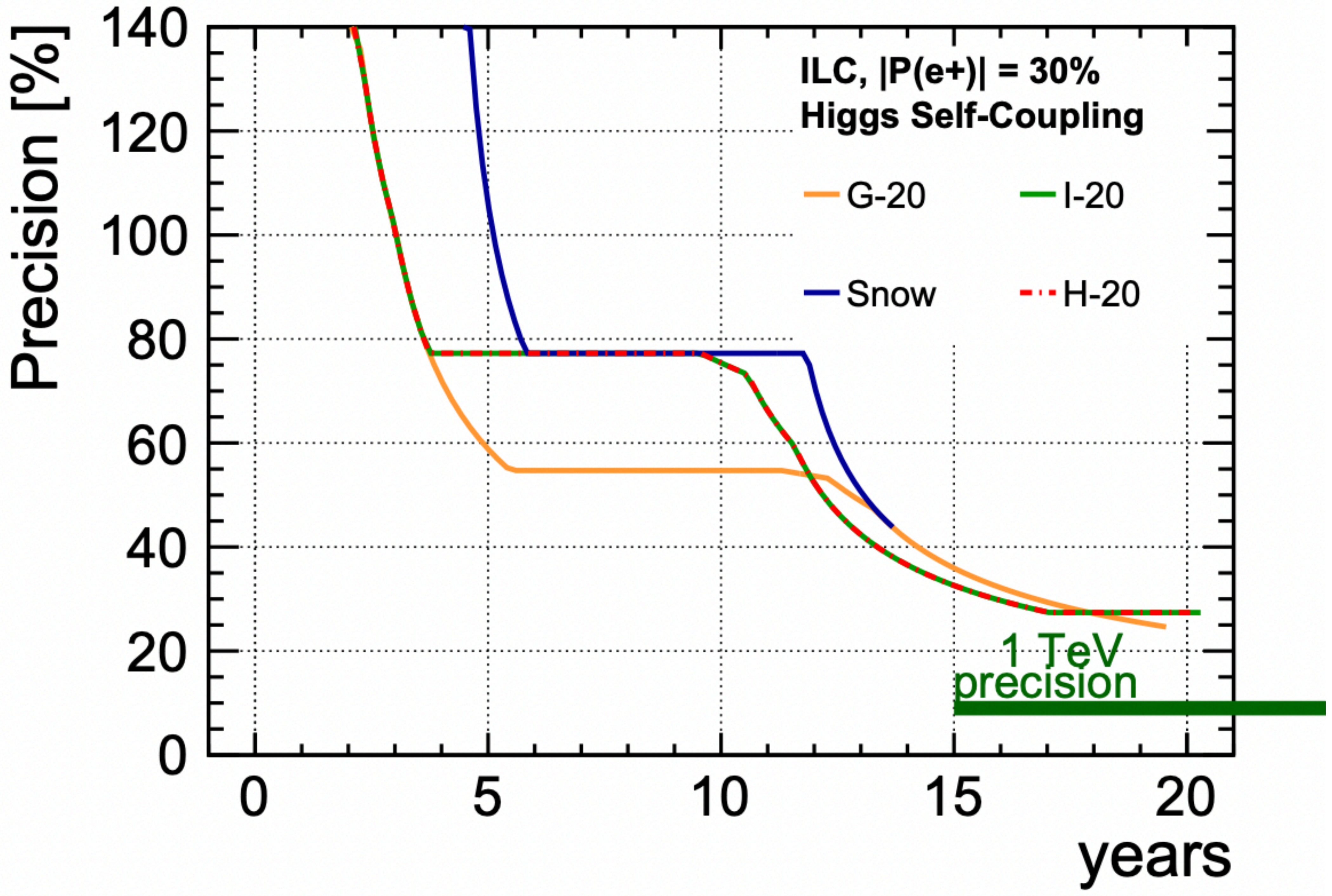
EF04 link

HL-LHC	3 ab-1 @ 14 TeV ATLAS+CMS (S2)				
prod.	ggH	VBF	WH	ZH	ttH
σ	-	-	-	-	
$\sigma x BR_{bb}$	19.1	-	8.3	4.6	10.2
$\sigma x BR_{cc}$	-	-	-	-	-
$\sigma x BR_{gg}$	-	-	-	-	-
$\sigma x BR_{ZZ}$	2.5	9.5	32.1	58.3	15.2
$\sigma x BR_{WW}$	2.5	5.5	9.9	12.8	6.6
$\sigma x BR_{\tau\tau}$	4.5	3.9	-	-	10.2
$\sigma x BR_{\gamma\gamma}$	2.5	7.9	9.9	13.2	5.9
$\sigma x BR_{\gamma Z}$	24.4	51.2	-	-	-
$\sigma x BR_{\mu\mu}$	11.1	30.7	-	-	-
$\sigma x BR_{inv.}$	-	2.5	-	-	-
m_H	10-20MeV				

wishlist: correlation matrix; differential x-section is not included now, but can be considered if available

Accuracy vs. Luminosity





	Stage	500			500 LumiUP		
Scenario	$\sqrt{s}$ [GeV]	500	350	250	500	350	250
G-20	$\int \mathscr{L} dt$ [fb^{-1}]	1000	200	500	4000	-	-
	time [years]	5.5	1.3	3.1	8.3	-	-
H-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	-	1500
	time [years]	3.7	1.3	3.1	7.5	-	3.1
I-20	$\int \mathscr{L} dt$ [fb^{-1}]	500	200	500	3500	1500	-
	time [years]	3.7	1.3	3.1	7.5	3.4	-